ACTA ORTHOPAEDICA SCANDINAVICA
SUPPLEMENTUM NO. 123

From the Department of Orthopaedic Surgery, University of Göteborg, Sweden.
(Head Professor Carl Hirsch)

MOTION IN THE CERVICAL SPINE

An Experimental Study on Autopsy Specimens

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MUNKSGAARD
Copenhagen 1969

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GÖTEBORG 1969

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ACKNOWLEDGEMENTS

This investigation was carried out at the Biomechanics Laboratory, Department of Orthopaedics, University of Gothenburg.

I wish to thank Professor Carl Hirsch, head of the Orthopaedic Department, for suggesting this subject to me, giving me the opportunity of working in the stimulating and unconventional atmosphere which he has created, and for his encouragement and interest.

During this investigation, problems obviously arose, and for the help in solving these I especially wish to thank Walter Brandt, Engineer, of AB Atomenergi, Studsvik, for his skilful work in designing the apparatus, Bernt Karlsson, B.A., for his patience in handling the data processing and Esbjörn Carlström, Ph.D., who supervised the statistical analyses.

I am also grateful to my colleagues for their interest, particularly Svante Rolander, Ass. Professor, who gave me impulses and good ideas, Hans Hellström, Engineer, for his valuable assistance, Mrs Eivor Rhedin, Mrs Inga-Lisa Elzer, and Miss Lena Johnsson for technical and secretarial work.

This investigation was supported by grants from:

The Swedish Medical Research Council,
The University of Gothenburg,
The Medical Society of Gothenburg,
The Carin Trygger Memorial Fund,
King Gustaf V Jubilee Fund,
The Swedish Labour Market Insurance Society,

Gothenburg in March, 1969.
ERLAND LYSELL

INTRODUCTION

Many people are occasionally or repeatedly subjected to pain and impaired motion in the neck, often combined with radiating pain in the back of their head, shoulders, arms or chest. In a Swedish population, the percentage was stated to be 70 (*Hult*, 1954).

These symptoms have been ascribed to various types of congenital, degenerative, or post-traumatic changes of the cervical spine. During latter decades numerous investigations have been published on the pathomorphology, diagnostics and therapy.

The diagnosis, to the greater part, was often based on studies of the function of the cervical spine. It has been maintained that changes in the function either would be the cause of the disturbances or signs of processes which could result in pain. However, on perusal of the literature, the information found about the normal function and its relation to degenerative changes is sparse. This particularly applies to the pattern of motion.

The purpose of this investigation was mainly to illustrate the normal pattern of motion and its variations due to degenerative changes, by studying the possibilities of motion in an autopsy specimen series. This study included all the interspaces between the second cervical vertebra and the first thoracic vertebra.

TERMS AND DEFINITIONS

The terms and definitions mentioned below, have been used throughout:

The cervical vertebrae are numbered in the conventional way C2–C7.

The first thoracic vertebra is designated Th1.

An interspace is identified by the numbers of the two surrounding vertebrae, for instance C4/5.

The motion of a segment is identified by the number of the vertebra above, and the motion of this vertebra is always related to the subjacent one.

Extension is equal to the motion in the sagittal plane, dorsally directed.

Flexion is equal to the motion in the sagittal plane, ventrally directed.

Latero-flexion is equal to the motion in the frontal plane to the right or the left.

Rotation is equal to the motion in the horizontal plane to the right (clockwise) or to the left (anti-clockwise).

The measuring points are designated A=anterior, P=posterior, R=right and L=left.

For statistical analyses, the Student's T-test was used when no other indication is given.

REVIEW OF LITERATURE

A. Earlier Methods for Measuring Intersegmental Motion in the Spine

1. *Motion Studies on Autopsy Specimens*

Ever since Galenus' and Vesalius' time, the motion of the spine has been studied. This survey is limited to the, in principle, different methods, reported and employed for intersegmental measurements of motion. For a comprehensive review of the literature, the reader is referred to *Elward* (1939) and *Andersson & Ekström* (1940).

The first real measurements were performed by *Weber* (1827). In three spinal specimens he dissected the spinal and transverse processes, and inserted metal pins, and then studied the motion of the pins while bending and stretching the specimens manually. The method of measuring angles or distances between pins inserted in the vertebrae has since then been employed repeatedly, inter alia, by *Volkman* (1872), *Meyer* (1873), *Hughes* (1892), *Lovett* (1905), *Keene* (1906–07) and *Lucas & Bresler* (1961). *Ball & Meijers* (1964) used the method to study the cervical spine. They radiographed the specimen at maximal flexion and extension, and measured the angle between the pins on the radiographs.

Virchow (1928) studied the motion of the cervical spine in the sagittal plane in two specimens by making plaster impressions of the specimen in a neutral position, and in manually caused flexion and extension. The specimens were macerated and split in the sagittal plane and placed in the different plaster impressions, and the range of motion could be measured. *Novgorodsky* (1911) on four specimens, demonstrated the intersegmental range of motion by testing the entire spine, step by step as follows. A vertebra was fitted to a measuring apparatus and the superjacent vertebra was secured in a movable ring, equipped with dials which indicated the motion at load in different directions.

The same method, in principle, was used by *Andersson & Ekström* (1940) for measuring motion in three thoracic and lumbar spine specimens. The recording was performed by means of a light ray which in small mirrors on the movable ring was reflected to a scale. Simultaneously, the magnitude and direction of the loading force were recorded.

Werne (1957) analysed the pattern of motion in the occipito-atlanto-axoid joints by reading the movement direct on protractors, fitted to the specimen.

The most accurate measurements of intersegmental motion were carried out by *Rolander* (1966). For his experimental study of the pattern of motion in the lumbar spine and the stabilizing effect of fusions, he used extensometers, the movements of which were recorded by differential transformers.

2. *Motion Studies on Living Subjects*

Direct measuring on living subjects by employing different types of goniometers, generally fitted to the head, cannot and are not intended to reveal the motion of the individual segments. This applies even if, for instance, *Stookey* (1966–67) believed himself capable of determining intersegmental impairment of motion, merely by means of manual examination. Attempts have been made to record the motion of the individual vertebrae by fitting various types of indicators to the skin over the tips of the spinal processes (*Löhr*, 1890; *Lovett*, 1905). For several reasons this method must be extremely inaccurate and, according to *Löhr* (1890), was not suitable for the cervical spine due to the comparatively great distance between the spinal processes and the skin.

Radiography has, so far, proved to give the best results when studying the motion of the spine in vivo. *Virchow* (1928) was one of the first to use this procedure. As a supplement to his earlier described investigation on specimens, he examined one person by means of radiography. Two radiographs were taken of the cervical spine, one in flexion and one in extension. From the radiographs, he copied the vertebral bodies and the pedicles on a paper. After selecting suitable measuring points, he connected them by drawing lines. When the two copies were placed on top of each other, the deviating angles of the lines, as seen on the copies, could be measured. *Dittmar* (1930) used the same method for the entire spine. He completed the examination with a radiograph in neutral position and studied the latero-flexion in the same way.

In principle, the same method was then used by many authors, and has been called "functional radiographic examination" or "Functionelle Röntgenuntersuchung" (*Penning*, 1968; *Schmorl & Junghanns*, 1951). The method of estimating the motion varies. *Bakke* (1931) drew lines through the upper and lower contours of the vertebral bodies. If the endplates of the vertebral bodies appeared as ellipses, he used their major axes as a measuring line. The maximum error was stated to be 2°.

Buetti-Bäuml (1954) used carbon paper to copy the contours of two vertebrae from the flexion radiograph to the extension radiograph, and was careful to superimpose the two lower contours. The position of the upper two vertebrae corresponded to the motion. Lines were drawn through the posterior contour of the vertebral bodies and the angle between these lines indicated the range of motion.

For clinical use, *Penning* (1968) placed a smaller film of the extension radiograph on top of the larger flexion radiograph. The contours of the two C7 views were made to coincide, and he drew a line along the edge of the top film. This procedure was repeated for each vertebra. The angles formed between the lines represented the intersegmental range of motion.

Albers (1954) expressed the total motion of the cervical spine in the angle formed between two lines drawn through the posterior contour of C7 and C2. The intersegmental motion was illustrated by indicating the angle between the vertical axis of C7 and a line drawn from the point of intersection of this axis and the upper endplate of C7 to the centre point of the lower endplate of each vertebra. *Schalimtzek* (1958), who measured the motion of the lumbar spine in the sagittal and frontal planes, drew lines through the distal contour of the bodies. *Kottke & Mundale* (1959) used the same method in principle for the cervical spine, while *Colachis & Strohm* (1965) measured the distance between the anterior and posterior corners, respectively, of the adjacent vertebral bodies. This is a mode of recording extension and compression of the anterior and posterior parts of a disc in connection with motion. By means of cine-radiography, the ranges of motion in the atlanto-occipital and the atlanto-epistrophic articulations were measured (*Fielding*, 1957). Accurate measurements were difficult to carry out, however, due to the ever-changing view and the enlargement (*Fielding*, 1964; *Hirsch et al.*, 1964; *Penning*, 1968).

B. Pattern of Motion in Cervical Spine

The pattern of motion in the cervical spine depends on the structure and shape of the discs and the intervertebral joints, and the combinations of the changed positions which may appear. The system is also affected by the ligaments and the joint capsules. Thus, *Ball & Meijers* (1964) found close correlation between the range of motion and the extensibility of the posterior soft collagen structures.

In relation to its surface, the cervical disc is comparatively high, which according to *Fick* (1911) partly explains the large range of motion as compared to other parts of the spine. The two vertebral endplates are cranially convex in the sagittal plane, and caudally convex in the frontal plane, and together with the disc form a saddle syndesmosis (*Fick*, 1911).

The surfaces of the intervertebral joints are almost perpendicular to the sagittal plane (*Fielding*, 1964; *Penning*, 1968) and the mean inclination to the frontal plane is 45°. The cranial facets are directed backwards-upwards and the caudal forwards-downwards. The joint capsules are easy to extend and permit great mobility.

The following description of the pattern of motion is based on published reports of a few anatomical specimens (*Winslow*, 1730; *Weber*, 1827, *Fick*, 1911) and radiographs of subjects. With the exception of cineradiographic examinations (*Fielding*, 1957 and 1964; *Jones*, 1960) the reports are based on exposures in extreme positions and in a neutral position (*Dittmar*, 1931; *Bakke*, 1931; *Hadley*, 1944 and 1956; *Exner*, 1954; *Buetti-Bäuml*, 1954; *Colachis et Strohm*, 1965; *Penning*, 1968).

In flexion a cervical vertebra tilts and slides forward over the subjacent one. There will then be a ventral compression and a dorsal expansion of the disc. The spinal processes are separated from each other and spread like a fan. Simultaneously, the caudal intervertebral joint surface of the vertebra slides upwards-forwards over the cranial joint surface of the subjacent vertebra. The joint space widens into the shape of a wedge with the base in a dorsal direction.

Most authors found that the tilting and sliding occurred at the same time. However, *Jones* (1960) reported that flexion began with the tilting and the sliding followed later. In extreme flexion, the joint facets were almost subluxated (*Fielding*, 1957) while *Penning* (1968) mentioned that they covered each other at least 5 mm.

When the cervical spine was extended, the pattern of motion was reversed. On the other hand, *Dittmar* (1931) stated that the C6 pattern was inverted, inasmuch as at flexion it slid backwards and at extension forwards over C7.

The sliding, combined with tilting, caused the anterior and the posterior borders of the vertebral bodies in extreme positions to form an uneven curve, and instead appear in a stepped shape. This sliding was normal in the cervical spine, but was believed to be a sign of disc degeneration in the lumbar spine (*Knutsson,* 1944).

The centre of motion is according to most authors, placed in the body of the subjacent vertebra, as opposed to other portions of the spine in which it is believed to lie in the disc (*Fick,* 1911). According to *Fick* (1911) and *Strasser* (1913), the axis is in the centre of the vertebral body. *Penning* (1968) mentioned that the axis of C2 is found in the postero-caudal portion of the body of C3, but in the lower portions of the cervical spine its position gradually becomes more anterio-cranial. The axis of C6 lies in the centre of the upper C7 endplate. When *Dittmar* (1931) tried to construct the axis of motion, he assumed it to lie within the disc. Thus, he obtained different axes for different parts of motion. *Exner* (1954) and *Hjortsjö* (1959) maintained that the axis is placed in the nucleus, but according to *Exner* the nucleus moves towards the convex side during motion, thus the axis of motion also moves. This seems to fit *Rolander's* (1966) findings of a very large number of motion centres in the lumbar spine.

The movements in the frontal and horizontal planes are dependent on each other, as latero-flexion always is combined with rotation in the same direction and vice versa (*Lovett,* 1905; *Novgorodsky,* 1911; *Dittmar,* 1931; *Exner,* 1954; *Buetti-Bäuml,* 1954; *Fielding,* 1964; *Hinz & Erdmann,* 1967; *Penning,* 1968).

When a vertebra is latero-flexed, the disc on the concave side is compressed, and expanded on the convex side and simultaneously distorted. On the concave side, the caudal intervertebral joint surface slides backwards-downwards and is pressed against the subjacent joint surface. On the convex side the joint surface slides upwards-forwards, and the joint space widens. *Bakke* (1931) mentioned that the vertebral body in latero-flexion slides on the disc slightly towards the convex side.

Even if the range of motion is reported merely as latero-flexion or rotation, the combined motion is optimal (*Hjortsjö,* 1959). *Fick* (1911) studied the planes of the intervertebral joints and found that an assumed line in the sagittal plane between the joint surfaces, perpendicular to them would pass through the centre of the subjacent vertebral body. He believed this line to be the axis of combined motion, the total range of motion around the axis amounting to 180°. *Novgorodsky* (1911) found that in two specimens, the range was 76° and 154°, respectively.

The lateral portion of the cervical spine, the so-called unco-vertebral region, with the uncinate process thrusting upwards from the lateral portion of the upper endplate, differs in shape from other portions of the spine.

It has been maintained that this region is a true synovial joint (*Trolard*, 1893; *Compere et al.*, 1958–59; *Jackson*, 1965). Most investigators, however, are aware of the fact that changes simulating a joint, merely are very early fissures formed laterally in the annulus (*Töndury*, 1943, 1959; *Hall*, 1965; *Ecklin*, 1960; *Hirsch et al.*, 1967). These fissures may be an adaptation caused by motion in that area (*Töndury*, 1943). The degenerative changes appear first in the cervical discs in this region (*Hirsch et al.*, 1967).

The uncinate process may be of importance for the pattern of motion in the cervical spine. It has been mentioned that the process prevents lateral or backward subluxation, and serves as an obstacle of latero-flexion. At the same time it acts as a guide rail for extension-flexion (*Frykholm*, 1951; *Compere et al.*, 1958–59; *Ecklin*, 1960; *Penning*, 1968).

C. Range of Motion in Cervical Spine

The cervical spine is the most mobile portion of the spine. The mean range of motion is according to *Hjortsjö* (1959): extension 55° (if the motion between the occiput—C1–C2 is included, 70°) flexion 65° (80°), latero-flexion 15° (20°) at each side and rotation 45° (70°) in either direction. The individual variations are very large.

Measurements of motion were generally based on a neutral position. In specimens the neutral position was called "Eigenform" (*Fick*, 1911), and was defined as the position of the cervical spine when it is unloaded and deprived of all musculature. The existing lordosis is believed to depend on the wedge-shape of the discs with an anterior base and on the vertebral bodies being higher ventrally than dorsally.

The neutral position of living individuals is difficult to define. Many authors claimed that in the neutral position, the vertebral bodies are situated in a symmetrical lordotic curve (e.g. *Hadley*, 1949). *Albers* (1954) and *Zeitler & Markuske* (1962) found different types of neutral positions in different individuals. There is also a straight shape of no pathological significance. *Fineman et al.*, (1963) showed that the normal lordotic pattern may be changed into a linear or kyphotic shape, merely by lowering the subject's chin slightly at the examination. A comparison between different authors requires an accurately defined neutral position. However, this is not the case. *Albers* (1954) and *Dittmar* (1931) stated a comfortable position. *Penning* (1968) pointed out that the lower margin of the orbita should lie in the same horizontal plane as the external auditory meatus. *De Sèze et al.*, (1951) preferred that the occlusion plane of the teeth should be horizontal, while other authors do not define the neutral position. This variation may explain differences and statistical contradictions when the range of motion is classified in extension and flexion (Table 1). *Bakke* (1931) measured the extension to be four times the flexion while *Kottke et al.* (1959) reported the flexion as slightly larger than the extension.

The occipito-atlanto-axoid joints were obviously included in the clinical examination of patients. Using goniometers of different types (*Bennet et al.*, 1963; *Buck et al.*, 1959) or other technical devices (*Volkmann*, 1872; *Ferlic*, 1962; *Schoening et Hannan*, 1964) mean values were obtained, on the whole, in accordance with those of *Hjortsjö* (1959).

In order to demonstrate the intersegmental range of motion, the most common method is to measure on radiographs. Views of extreme extension and flexion and sometimes also a neutral position view have been compared. Most authors expressed the total motion in the change of angle between the sagittal diameters of the top and the bottom vertebrae. Others used the angle which is described by a line between the anterior corner of Th1 and C2 (*Colachis & Strohm*, 1965) or the distance between the tips of the spinal processes (*Otto*, 1955; *Rössler & Schmeisser*, 1957–58). The results of the various methods are difficult to compare.

An assessment of the entire cervical spine motion is for several reasons not sufficiently informative (*Kottke & Mundale*, 1959). Segmental immobilization due to post-traumatic or degenerative changes, for instance, may often increase the mobility of adjacent segments (*Fielding*, 1964). The intersegmental ranges of motion, as reported in the literature, are tabulated (Table 1). The few investigations carried out, to the greater part deal with positions in the sagittal plane.

The examinations of specimens are few and mainly of an early date. The range of motion in the sagittal plane was measured on 18 specimens, in the frontal plane on 5, and in the horizontal plane on 6 specimens.

It is difficult to compare the results as the methods differ, and as no details are given about the specimens. *Ball & Meijer* (1964) who were responsible for half of the published series dealing with measurements in the sagittal plane, radiographed the specimens in one plane. They have not eliminated the sources of error which could be involved with this procedure.

The intersegmental motion on living subjects was measured on radio-

Table 1. Range of motion

Author	Year	No.	Age	C2 Ext.	C2 Flex.	C2 Total		C3 Ext.	C3 Flex.	C3 Total		C4 Ext.	C4 Flex.	C4 Total	
EXTENSION FLEXION				Ext.	Flex.	Total		Ext.	Flex.	Total		Ext.	Flex.	Total	
Measurement on specimens															
1 Weber	1827	3	?	almost none				very big				very big			
2 Virchow	1928	2	?	4–6	3–7	7–13		3	5.5–9	8.5–12		7–9	7.75–8	15–16.75	
3 Novgorodsky	1911	4	53–62			12–18				11–21				8–14	
4 Ball & Meijers	1964	9	21–70			(4.5–12.5)	9.5			(7–20)	15.1			(12.5–28)	18.1
Measurement on radiographs of living subjects															
5 Virchow	1928	1	?				16				20				20
6 Dittmar	1931	?	?	1.5	9		10.5	17	16		23	15	7		22
7 Bakke	1931	15	13–61	9.6	3.0		12.6	12.3	3.1		15.4	12.3	2.8		15.1
8 Buetti-Bäuml	1954	30	10–40			(5–18)	10.5			(13–23)	17			(16–28)	21
9 Exner	1954	4	18–58			2.5–13				9.5–22.5				8.0–28.5	
10 De Sèze & al.	1951	9	15–55	8	5		13	10	5.5		15.5	12	7		19
11 Kotke & al.	1959	78	young men	3	8		11	9	7		16	8	10		18
12 Zeitler &		24	11–14			(18–23)	17.5			(15–38)	25.5			(22–39)	29.5
Markuske	1962	24	15–18			(4–22)	13.5			(13–29)	21			(10–31)	22.5
13 Penning	1968	?	?			(5–16)	12.5			(13–26)	18			(15–29)	20
LATEROFLEXION				Right	Left	Total		Right	Left	Total		Right	Left	Total	
Measurement on specimens															
14 Meyer	1873	1	23	7°22′	6°38′		14°	4°20′	6°47′		11°07′	5°12′	6°48′		12°
15 Novgorodsky	1911	4	35–62			11–20				9–15				0–16	
Measurement on radiographs of living subjects															
16 Dittmar	1931	1	?	4.5				3.5				3.5			
17 Bakke	1931	5	13–23	3.5				4.8				4.5			
ROTATION						Total				Total				Total	
Measurement on specimens															
18 Hughes	1892	2	20–?				28.2				27.7				25.7
19 Novgorodsky	1911	4	35–62			12–23				9–14				0–12	

	C5				C6				C7				Sum C2–C6			
	Ext.	Flex.	Total		Ext.	Flex.	Total		Ext.	Flex.	Total		Ext.	Flex.	Total	
1	very big				small				very small							
2	2–6.5	9.5–13.25	15.25–16		1–2	7.5–15.5	8.5–17.5		4	5.75		9.75				
3			9–17				8–14				8–12					
4			(14–25)	20.2			(14–24)	17.6			(6.5–17)	10.4				80.5
5				—				—				—				—
6	16	10.5		26.5	10.5	13.5		24.0				—	60.0	46.0		106.0
7	16.6	3.8		20.4	13.4	3.6		17.0	6.2	4.0		10.2	64.2	16.3		80.5
8			(18–28)	22.5			(13–25)	18				—				89.0
9			4.5–23.5				1.0–25.5					—			25.5–104.5	
10	18.5	9		27.5	11	6.5		17.5				—	58.5	33.0		91.5
11	11	10		21	5	13		18				—	36	48		84
12			(20–34)	27.5			(17–29)	23				—				123.0
			(10–29)	23			(13–29)	21.5				—				101.5
13			(16–29)	21.5			(6–25)	15.5			(4–12)	8				87.5
	Right	Left	Total		Right	Left	Total		Right	Left	Total		Right	Left	Total	
14	5°55′	2°49′		8°44′	5°07′	3°58′		9°05′	4°55′	5°55′		10°50′	27°56′	27°		54°56′
15			0–16				0–17				0–17					
16	1.0				0.5								13			
17	5.0				4.0				2.8				21.8			
			Total				Total				Total				Total	
18				33.8				15.3				13.0				130.7
19			0–13				0–14				0–13					

graphs. The table shows that the largest range of motion in the sagittal plane almost regularly was found between C5–C6. This was verified by other authors omitting statistical data (*Hadley*, 1949; *Fielding*, 1957; *Colachis & Strohm*, 1965). There is a considerable individual dispersion within the various segments, often more than 10° within one segment. The reason may be that the intersegmental range of motion depends on the mode in which the movement is performed. *Jones* (1960) showed that the range varied if the flexion was begun or ended by drawing in the chin. Despite projection and method errors, the values indicated for the intersegmental total range of motion, however, seem to be in comparatively good accordance.

Intersegmental measurements of motion on radiographs are extremely inaccurate with respect to other directions except for the sagittal plane. This is illustrated by the fact that with two exceptions, no numerical data are given. *Dittmar's* (1931) values were published merely as notes on a sketch. *Penning* (1968) stated that the total latero-flexion in one direction was 30°, but that it was unevenly distributed over the segments. He indicated the rotation at 8–10° per segment.

D. Degenerative Changes and Motion

Degenerative changes of the cervical spine begin very early and are primarily localized to the annulus fibrosus in the unco-vertebral region. The uncinate process is not developed during the first years of life, but begins to grow at the age of 6–9 years and is fully developed at the age of 18 years (*Rathke*, 1933/34). Already at 4 years of age (*Hall*, 1965), and at 7 years of age (*Hirsch et al.*, 1967) fissures in this area were demonstrated, and signs of degenerative changes are obvious at the age of 14 years. These early changes may be explained by the fact that the disc and the annulus fibrosus are avascular tissues from birth (*Hirsch et al.*, 1967). As the disc in this area is very thin and the sliding movement in the sagittal plane is large, there is a predisposition to fissure formation (*Frykholm*, 1951). Changes resembling osteo-arthritis are common in the unco-vertebral region, and according to *Krogdahl & Torgersen* (1940), they may occur without synchronous changes in other parts of the disc.

Hirsch, Schajowicz & Galante (1967) described the course of disc degeneration in the cervical spine on a series of 111 autopsy specimens. The first stage consisted of fissures in the disc, surrounded by pronounced vascularized connective tissue. Then osteophytes appeared ventrally and postero-laterally. Finally, the height of the disc decreased and changes occurred in the cartilaginous endplate and the subchondral bone. Vessels infiltrated the disc which gradually was replaced by connective tissue, thus, forming a fibrous anchylosis between the vertebral bodies.

The degenerative changes become more severe with increasing age, but sometimes grave changes can be observed in young individuals or small changes in old persons (*Silberstein*, 1965). The changes in the disc appear earliest, and become most pronounced in the C4–C6 interspaces (*Payne & Spillane*, 1957; *Hadley*, 1956; *Ecklin*, 1960; *Silberstein*, 1965; *Hirsch et al.*, 1967) where the range of motion, anyhow in the sagittal plane, is largest. This has been taken as a sign of mechanical factors causing or accelerating degenerative changes (*Hadley*, 1949, 1956).

The degenerative changes in the intervertebral joints follow the classical pattern of osteo-arthritis (*Hirsch et al.*, 1967). They are most common in the upper and middle portions of the cervical spine (*Holt & Yates*, 1966). There is no correlation between the frequency or the degree of disc degeneration and osteophytes in the first place, and secondly of osteo-arthritis in the intervertebral joints (*Payne & Spillane*, 1957; *Friedenberg et al.*, 1959; *Hirsch et al.*, 1967). There is a general consensus of opinions about the total motion of the cervical spine decreasing with age (*Blanchard & Kottke*, 1953; *Rössler & Schmeisser*, 1957/58; *Jones*, 1960; *Zeitler & Markuske*, 1962; *Schoening & Hannan*, 1964), and that increasing degenerative changes in the disc result in a proportionally decreased intersegmental motion (*Hadley*, 1944; *Jones*, 1960; *Ball & Meijers*, 1964; *Fielding*, 1964). On the other hand, a locally reduced motion caused by degeneration or post-traumatic changes in one segment, results in a compensatory increase in the motion of adjacent segments (*Jones*, 1960; *Fielding*, 1964). Consequently, disc degeneration must exist in more than one segment to affect the total motion (*Schoening & Hannan*, 1964).

Osteo-arthritis of the intervertebral joints could affect the range of motion, but *Schoening & Hannan* (1964) found no correlation between the range of motion and the degree of osteo-arthritis or the number of engaged levels. Although the frequency and degree of osteo-arthritis are highest in the upper intervertebral joints, *Jones* (1960) also found that the motion is proportionally greater in the upper part of the cervical spine when, in high ages, changes of the disc in the middle and lower parts caused impairment of mobility.

OWN INVESTIGATION

A. Method

1. *Discussion of Measuring Methods*

Even if the motion, expressed in degrees, is large within the cervical spine, the linear motion between the segments is small. Assuming that *Penning's* (1968) construction of the centre of motion is correct, a point at a distance of 20 mm from the centre would change its position only about 0.8 mm which corresponds to an angular motion of 2°. Approximately, 20 mm corresponds to the distance from the centre of motion to the anterior border of the superjacent vertebra. For instance, if the total range of motion in a segment is 20°, a linear error in measurement of only 0.8 mm will result in an angular error of 10 per cent.

In order to get a correct idea of both the pattern and the range of motion, a method with small linear errors in measurement would be desirable.

The entire cervical spine moves as one unit in vivo. With the exception of the upper two interspaces, occiput—C1–C2, a segment never moves without a synchronous movement of the adjacent interspace. In order to maintain as normal a condition as possible, as well as the normal binding between the vertebrae, it seemed advisable to examine the entire cervical spine undivided. This meant that the synchronous motion of six interspaces, i.e. seven vertebrae had to be recorded.

Preliminary experiments revealed that a motion cannot be brought about which in the entire cervical spine is limited to one plane. Assuming that each vertebra is a rigid body, its position in space can be determined by means of a plane through the vertebra. The position of the plane is determined by three points in the plane, which are not in line and which can be reproduced in every position.

In a deliberate direction of motion each vertebra must be able to move freely.

The measuring method should thus cover the following demands:

1. small linear errors in measurement,

2. synchronous recording of a motion in space of at least 21 points (7 vertebrae each with 3 points),
3. the method must not restrict the motion,
4. reproducible measuring points.

Of the measuring methods earlier used on specimens of the spine, none fulfilled these demands. The use of steel pins, inserted into the vertebrae gives favourable results only if the motion occurs in one plane. Simultaneous measurements of angular changes in several planes, requires a large number of protractors fitted to the specimen which may result in restricted motion.

Virchow's (1928) method of plaster impressions, will cause slackness in the moulds when the specimen has been freed from the soft parts, resulting in linear errors in measurement. Methods involving stepped testing of the segments are adverse to the third demand.

Rolander's (1966) technique has the advantage of being very accurate, but applied to 21 measuring points it would require a considerable number of measuring devices fixed to the specimen which would restrict the motion.

Both functional radiographic examination and cineradiography are disadvantageous inasmuch as a three-dimensional course is reduced to a two-dimensional representation. The theoretical conditions which would allow the changed positions to be measured quantitatively, and with a high geometric quality, on radiographs exposed in one plane only, are:

a. that the motion occurs in one plane which is parallel with the roentgen film or that the angles to the film plane are known,
b. that the geometric relations between the focus, object and film are known, and
c. that within the object to be measured, there are well defined measuring points.

The first demand excludes measurement of latero-flexion and rotation in the cervical spine, as latero-flexion in a segment cannot occur without synchronous rotation and vice versa. Theoretically, the motion in the sagittal plane can be measured if its relation to the film plane is known. At each exposure it is necessary to know where each vertebra to be measured is situated in the film plane—roentgen tube system. For practical reasons, this is, of course, impossible.

As all examinations are based upon points selected in the contour of the vertebral body or the spinal process, this means that when measuring a point, it must be selected where a roentgen ray is a tangent to the vertebral surface. The vertebral body is demarcated by irregular surfaces. If a roentgen ray should be a tangent to a surface in the same point at different exposures, this means that the vertebra always should be in the same position in relation to the film and the focus of the roentgen tube. As the vertebrae move relative to each other, the tangent can strike only one vertebra in the same point, while the others have changed their position in relation to the roentgen ray. If as a point of measurement, the tip of the spinal process is used, which in most of the cervical vertebrae is double, it is impossible to know which of the tips forms the contour.

This method is, consequently, impossible to use for accurate measurements of motion, as the numerous sources of error are uncontrollable. *Buetti-Bäuml* (1954) illustrated this in practice by finding that the sagittal diameter of one and the same vertebra is not always equally long when measuring different roentgen films, despite "identical, technical conditions". Furthermore, when studying the published diagrams of motion (*Dittmar*, 1931) and the radiographs (*Penning*, 1968) it was found that the contour of a vertebra has not the same shape in different positions.

Despite this, the above method seems to be the most favourable, so far, for assessment of the intersegmental range of motion in clinical use, as long as the sources of error are borne in mind, and an error of measurement of 2° is not stated, at the same time as the range of motion is indicated in tenths of a degree.

The method selected, offers a three-dimensional radiographic examination at which fixed measuring points have been created by placing small steel balls in each vertebra.

2. *Apparatus*

On an approximately 2.5 m long stand, consisting of an I-beam, 20 × 20 cm, an object table and a roentgen tube are fitted (Fig. 1). The object table (*A*) is circular and rotatable around a vertical axis which runs through a reference point (*R*), which is a steel ball with a diameter of 0.8 mm and placed in a pillar of plexiglass. The object table can be locked in seven pre-set positions, middle position (pos. 0), at 30°, 22.5° and 15° each way, calculated from the middle position. For this investigation only the positions +22.5° (pos. I) and −22.5° (pos. II) were used. Perpendicular to the rotation plane of the object table there is a roentgen film holder (*B*) behind the reference point. The holder which is intended for a film size of 24 × 30 cm, can be parallelly displaced along an L-square ruler (*C*). The front of the holder consists of a per-

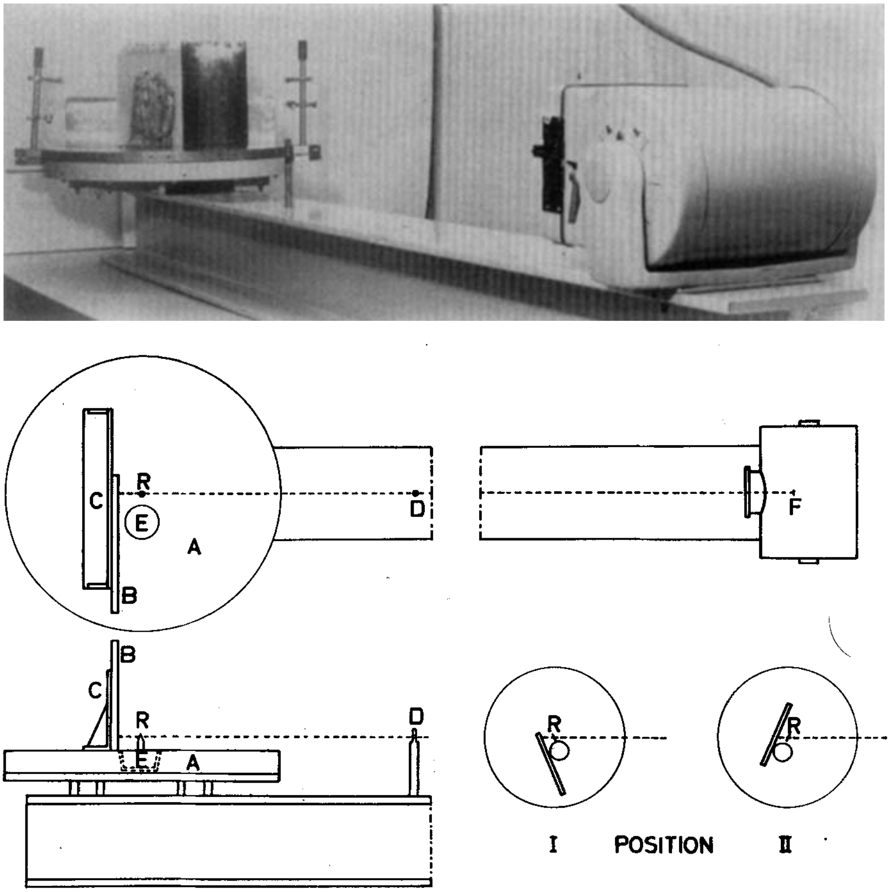
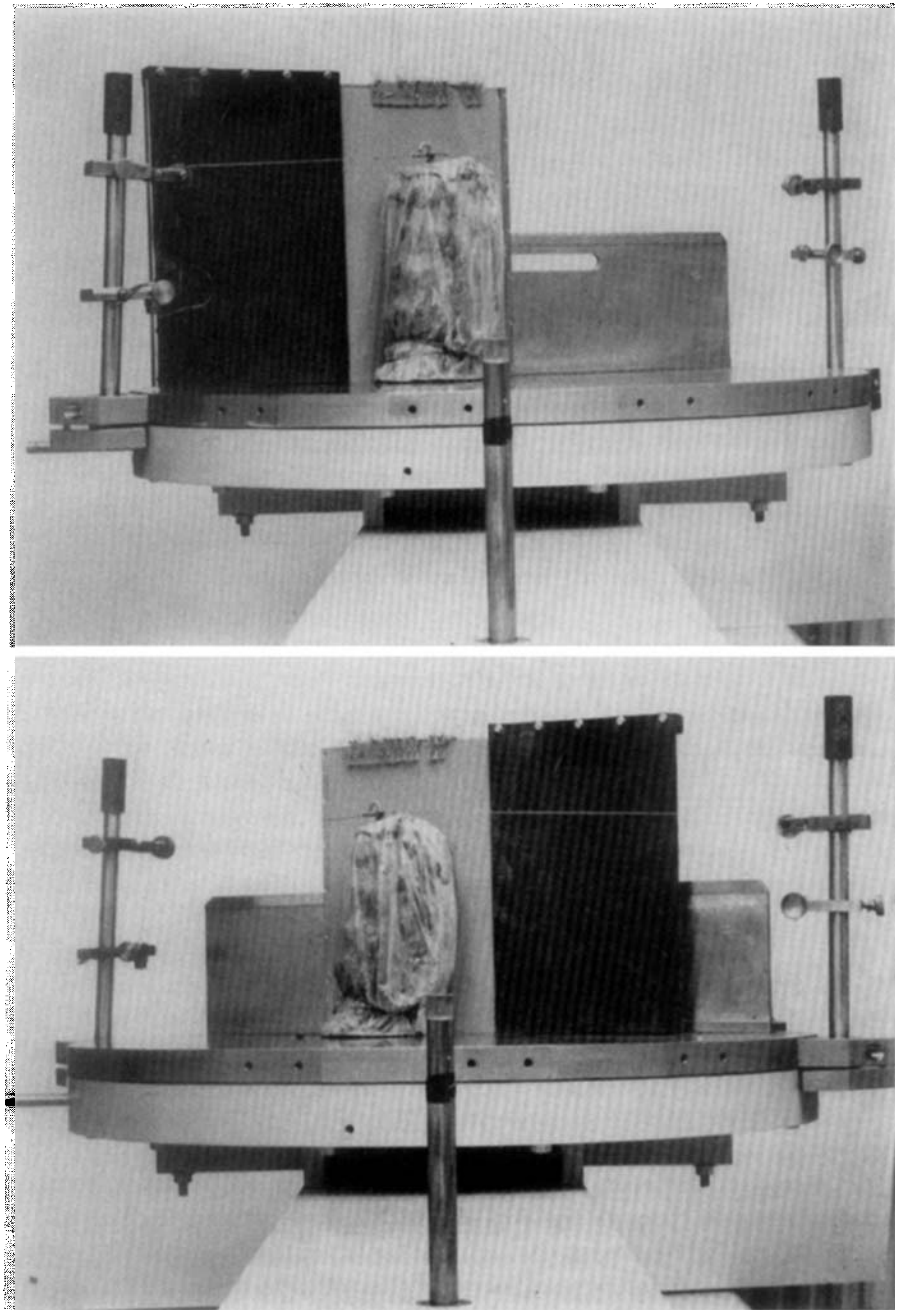


Fig. 1. The apparatus. For description see text.

forated, surface ground sheet steel and the roentgen film is fixed flat to this by means of partial vacuum (80 mm H_2O), achieved by a suction device.

In the object table and in front of the film holder there is a cavity into which a brass cup (*E*) can be placed and secured.

On the stand between the roentgen tube and the object table, there is a metal rod (*D*) through the top of which a bore was made. The rod is placed so that a line drawn through the centre of the bore and the centre of the reference point is parallel with the rotation plane of the object table and thus perpendicular to its axis of rotation and to the film plane in position 0.



A

B

Fig. 2. Object table with mounted specimen in position I (2A) and position II (2B). Views seen from focus of roentgen tube.

The roentgen tube is a standard model, Siemens Monodor SR 90/3/20, focus 0.6 mm. The attachment of the tube on the stand permits adjustment in all directions and locking in the desired position. Before measuring, the tube is fixed so that the reference point is projected in the centre of the projected bore on the roentgen film. This means that a roentgen beam (interrupted line) from the focus through the reference point strikes the film in position 0, perpendicularly, and is at right angles to the axis of rotation of the object table.

When examining the specimen which is fixed to the brass cup, the object table is first turned to position I (Fig. 2A), the film holder is moved to the left and the left part of the film is covered with a roentgen opaque shield, and the first exposure can be made. Then the object table is turned to position II (Fig. 2B), the film holder is displaced parallel to the right and the right part of the film is covered, ready for the second exposure. Between the exposures, the position of the specimen and the position of the film on the holder must not be disturbed.

3. *Geometry*

The zero point, in the primary, right-angled coordinate system is the reference point (*R*). The x-axis is parallel with the roentgen film, and the rotation plane of the object table in a positive direction to the left. The y-axis coincides with the rotation axis of the object table in a positive direction upwards. The z-axis is, consequently, at right angles to the film and parallel with the rotation plane of the table and coincides in position 0 with the central beam of the roentgen tube, and is positive in the direction towards the focus of the tube. The coordinate system follows the rotation of the table (Fig. 3).

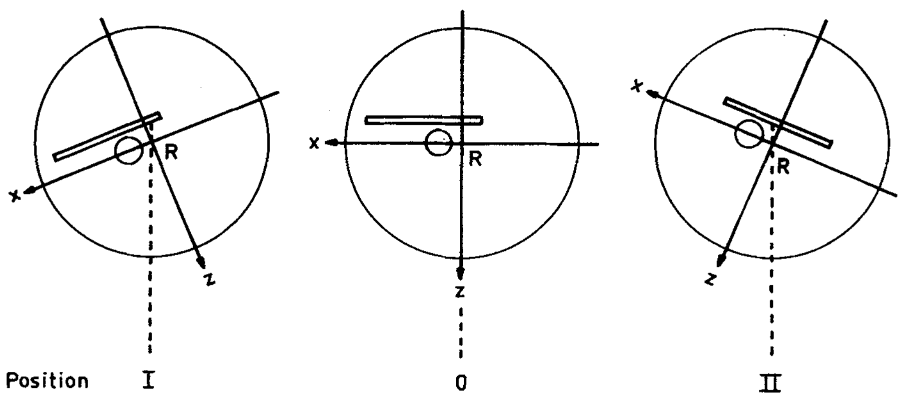


Fig. 3. Rotation of primary coordinate system with the object table. Dashed line runs towards focus of roentgen tube.

Fig. 4 depicts the following geometrical conditions. P is a point in the specimen, whose x-, y- and z-coordinates are searched. P' is the picture of P on the film in position I (P'' in position II). R' (R'' respectively) is the picture of the reference point. A is the projection of P in the xz-plane and F is the focus of the roentgen tube. V is the angle of rotation from position 0.

In position I the $PB'A$ plane in the pyramid $FP'R'A'$ is parallel with the base $P'R'A'$. Thus, the triangle $FA'R'$ is uniform with the triangle FAB' and the triangle $P'R'A'$ is uniform with the triangle $PB'A$.

$$\frac{FR'}{FB'}=\frac{A'R'}{AB'}=\frac{P'A'}{PA} \tag{1}$$

The same reasoning is applied to position II and gives:

$$\frac{FR''}{FB''}=\frac{A''R''}{AB''}=\frac{P''A''}{PA} \tag{2}$$

The distances $A'R'$ and $A''R''$, expressed x' and x'', and the distances $P'A'$ and $P''A''$, expressed y' and y'' are measured on the film. The distance from the reference point to the film plane is 50 mm (in the formula b mm) and the distance focus—reference point (FR) is 2000 mm (a mm). The angle of torsion, v, is 22.5°.

By using these values in the formulae (1) and (2) the following equations are obtained:

$$\frac{a+\dfrac{b}{\cos v}}{a-\dfrac{z}{\cos v}}=\frac{x'}{x-z\tan v}=\frac{y'}{y} \tag{3}$$

$$\frac{a+\dfrac{b}{\cos v}}{a-\dfrac{z}{\cos v}}=\frac{x''}{x+z\tan v}=\frac{y''}{y} \tag{4}$$

From the formulae it is seen that $y'=y''$. If this is not the case, the film has been moved on its holder or the specimen has been disturbed when shifting from position I to position II. Consequently, there is a control when measuring each film.

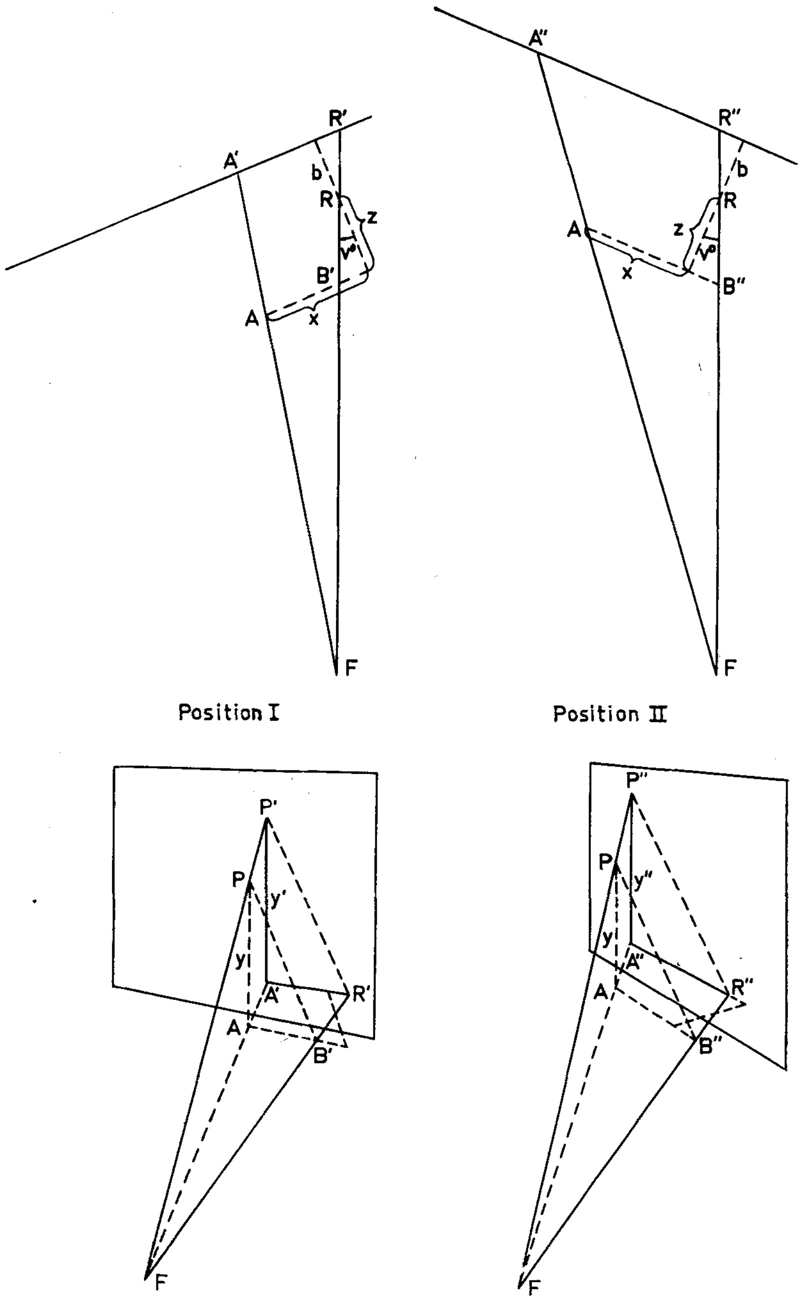


Fig. 4. Geometry of the apparatus. For description see text.

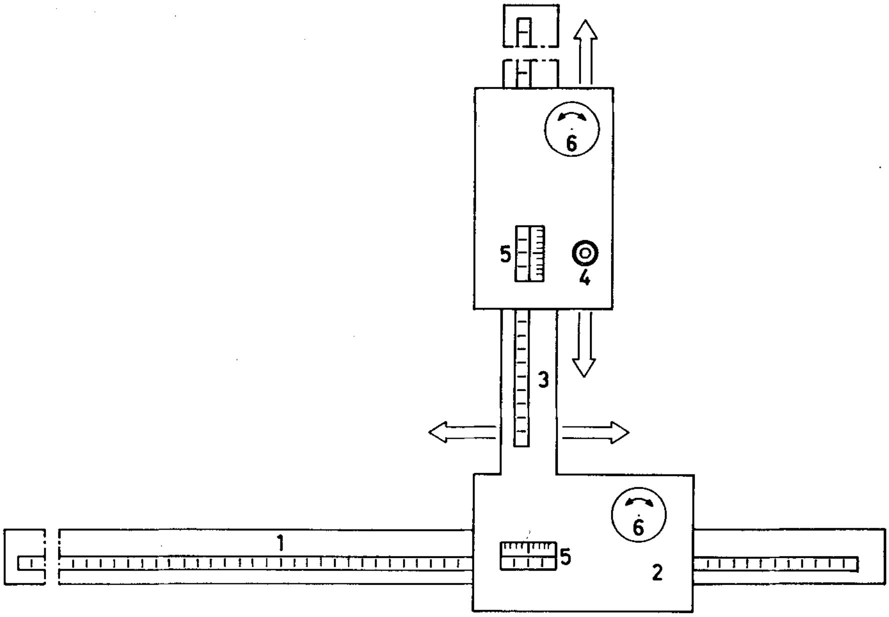


Fig. 5. Detail coordinatograph. Along an x-ruler (1) a metal slide (2) runs to which a y-ruler (3) is attached perpendicular to the x-ruler. Along the y-ruler another metal slide runs equipped with an ocular (4). The rulers are graded. The metal plates have vernier scales (5) permitting readings of ± 0.05 mm. Knobs (6) are used for moving the slides. The measuring point is adjusted in the ocular ring and the x and y values can be read. The arrows indicate directions of motion.

4. *Measuring on Radiographs*

The film is fixed with tape against a flat, horizontal glass plate which is transilluminated from below. The measurings are performed by the use of a detail coordinatograph (Fig. 5), the x-ruler of which is placed parallel with the line $R'R''$ and the values of points R' and R'' are noted. The height adjustment is checked during the entire measuring procedure by ensuring that y' and y'' are equal in each point. After all the points have been measured, it is made sure that the instrument has not been displaced laterally by re-measuring R' and R''. Part of the series was measured by the aid of a steroautograph. The instrument, used as a monocomparator, automically records the measuring values, and produces a punch tape which can be used for data processing. In principle, the measurements have been made in the same way and the time gained was considerable. The distances, measured on each film are shown in Fig. 6.

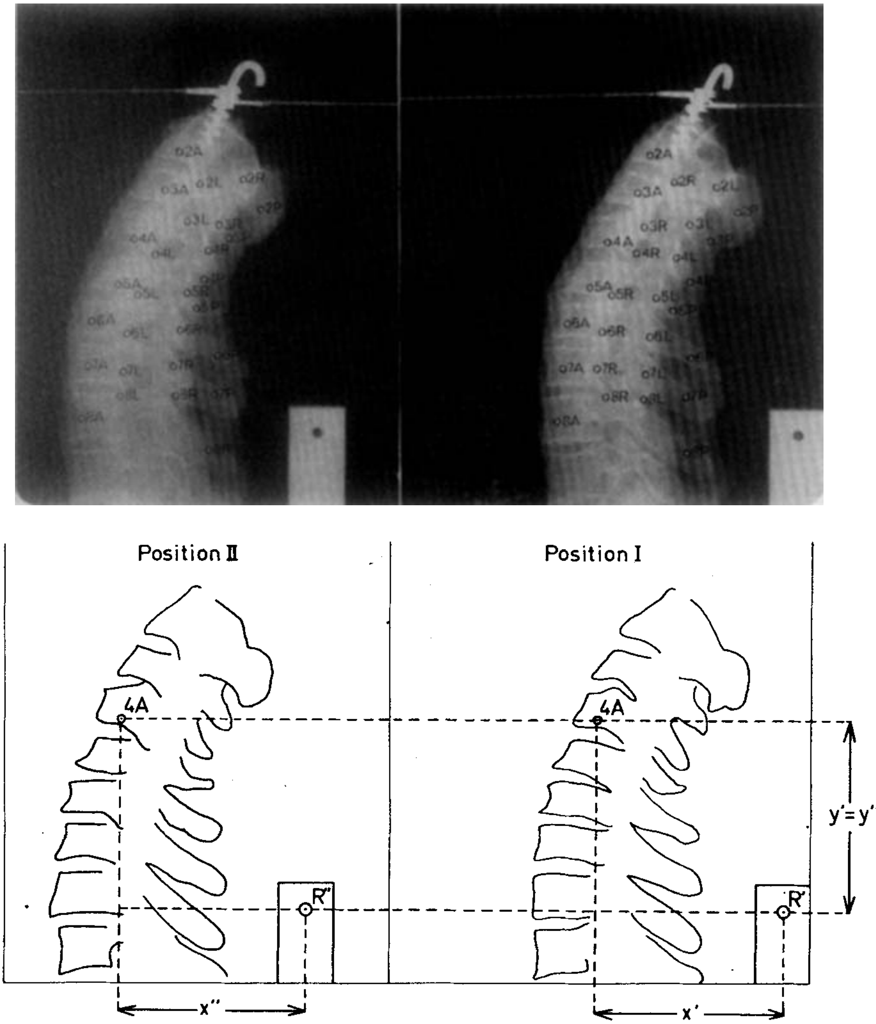


Fig. 6. Top view. Measuring points indicated on radiograph. Bottom view. Sketch of same radiograph, where measured distances are indicated. N.B. $y' = y''$.

5. *Treatment of Primary Data*

In the first place the primary measuring values x', x'' and y' (y'') are inserted in the formulae (3) and (4), from which the coordinates of each measuring point are obtained.

In the continued treatment it is assumed that each vertebra is a rigid body. In order to check that this is true, the angles between the planes, formed by the inserted four measuring points are calculated within each vertebra after each movement. These planes are: *ARP* and *ALP* and further *RLA* and *RLP*. If these control angles remain unchanged, this means that the vertebra is not deformed beyond the limits of error of the method. This is also a control that the primary measuring values are not erroneous, for instance, by incorrect notes, erroneous punching or mixing of the measuring points.

The cervical vertebrae are often asymmetrical and asymmetrically placed. Thus, the primary measuring points cannot be symmetrically arranged. In order to obtain a symmetrical and comparable neutral position, and to facilitate the study of the motion, four fictive secondary measuring points were assumed in each vertebra at the neutral position (see below). These were selected so that the *A* and *P* points lay in the *xy*-plane of the primary coordinate system, and on a line forming the projection in this plane of the line between the primary points *A* and *P*. The secondary measuring point *A* is the projection of the primary measuring point *A* in the *xy*-plane, and the distance between the secondary measuring points *A* and *P* was selected to be 40.0 mm. The secondary measuring points *R* and *L* form the end points of a line, 40.0 mm long, the centre point of which divides the *AP* line equally and is parallel with the *z*-axis of the primary coordinate system. Thus, the four secondary measuring points form the end points of two 40.0 mm long vectors, at right angles to each other, which lie in a plane with the same inclination towards the *xz*-plane, as the line between the primary *A* and *P*-points.

After each movement, the position of the secondary measuring points was calculated so that it remained unchanged in relation to the primary measuring points within each vertebra.

As the purpose was to illustrate the intersegmental motion, a secondary coordinate system was placed in each vertebra, using the two described vectors as two of the axes. In this coordinate system the secondary measuring points of the superjacent vertebra were calculated, thus obtaining their motion in relation to the subjacent vertebra (Fig. 7). These sterometric calculations mean a large number of mathematical operations, which have been performed by means of data processing.

6. *Preparation of Specimen and Testing*

According to *Hirsch & Galante* (1967), *Galante* (1967) and *Tkaczuk* (1968) the tensile properties of the annulus fibrosus and the longitudinal ligaments change if they are subjected to dehydration. This occurs if

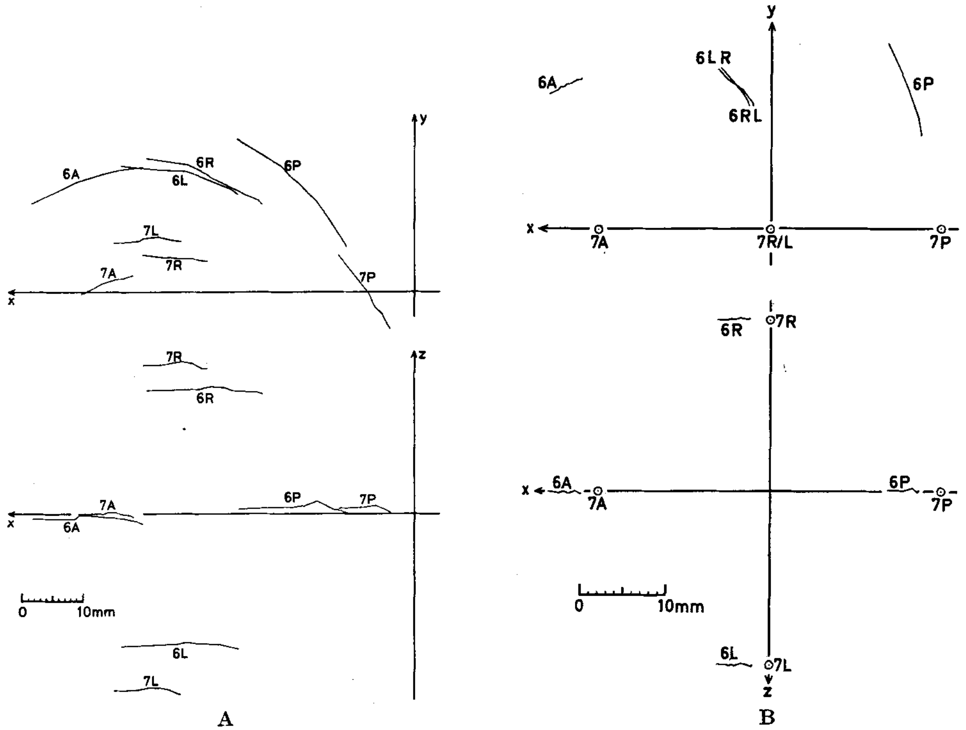


Fig. 7. Motion in a segment illustrated, using primary measuring points (A), using secondary measuring points (B) transformed into the secondary coordinate system.

they are not stored in an atmosphere close to a relative humidity of 100 per cent.

In order to protect the specimens in this investigation against dehydration, they were always stored in air-tight plastic bags. The specimens were always treated at room temperature (approx. 22°C) and very close to 100 per cent RH.

The specimen, consisting of an undivided spine from C2 up to and including Th2 or 3, was freed from musculature and other soft parts only so much that the necessary anatomical details could be identified. All the ligaments, joint capsules, and bone structures were maintained, and as a further protection against dehydration, a thin layer of musculature was left.

In each vertebra (C2–Th1) four steel balls (⌀ 0.8 mm) were inserted. The anterior (*A*) and the posterior (*P*) were inserted as closely to the sagittal plane as possible, and immediately subcortically in the anterior surface of the vertebral body and the spinal process, respectively. The two lateral balls (*R* and *L*) were inserted in the caudal intervertebral joint processes.

In the longitudinal axis of the dens epistrophei, a screw was inserted, the shaft of which resembles a hook. Through the vertebral body of C2, immediately below the cranial intervertebral joint surfaces, a transversal bore was drilled, through which a Kirschner wire could be inserted.

The two bottom vertebrae of the specimen were fixed in the brass cup (Fig. 1:E) with Plastic Padding—unsaturated polyester resin—(*Hirsch,* 1964) which was inserted into the cavity of the object table. One frontal and one lateral view were exposed in order to check the positions of the indicator balls. Then the cup was fixed so that the sagittal plane of the specimen would coincide as closely as possible with the *xy*-plane of the primary coordinate system. The specimen was now in a resting position and was not affected by any loading. One view, the neutral position, was exposed according to the earlier description.

By means of thin metal wires, attached to the screw in the top of the specimen, and adjustably fixed to lever arms in the periphery of the object table, the specimen was drawn backwards into extreme extension. From this point the entire motion was performed into extreme flexion in ten steps. One exposure was made between each step. The motion was then reversed in the same way. Consequently, the motion in the sagittal plane was divided into 19 steps.

The base of the specimen was rotated 90° and latero-flexion was performed from the extreme left to the extreme right and back in 13 steps. In the transverse bore in C2 a Kirschner-wire was inserted and via a clamp which allowed free play up and down, the specimen was rotated vertically. The rotation was performed from extreme left to extreme right in seven steps.

A total of 40 radiographs were thus obtained, each having 58 measurable points, i.e. 2300 points per specimen.

7. *Discussion of Method.*

The following sources of error exist

The apparatus: The projection of each ball strikes the film at an oblique angle, which means that the view of the ball will be elliptic. If the source of radiation were a point, the view of the ball would be sharply demarcated and its centre would correspond to the centre of the ball. However, as the focus of the roentgen tube is a surface, partial shading of varying dimensions, caused a diffuse image of the ball. Thus, the centre of the ball did not correspond to the centre of its image. However, a calculation of the discrepancy showed that it did not exceed 0.01 mm within the area to be measured. As the linear measuring results were not indicated with more than one decimal of a millimeter, this error was insignificant.

The geometric formulae (3) and (4) are based on the fact that parts of the apparatus which form the primary coordinate system are at right angles to each other. Within reasonable economical limits, this was achieved so that the angular error in no case exceeded one minute of arc. The error of angle of rotation was max. $\pm 0.5'$. These minor errors do not affect the first decimal in the result.

The distance focus—reference point (a in the formulae 3 and 4) is 2000 mm (max. error ± 2 mm) and the distance between the reference point and the film plane (b in the formulae 3 and 4) is 50 mm. (max. error ± 0.5 mm).

Primary data: The measuring values x', x'' and y' (y'') are dependent on the dimensional stability of the film and the error in the measuring instrument.

The roentgen film was made of polyester, the coefficient of expansion of which was for the temperature cm/cm/°C$=3.61\times 10^{-5}$ and for relative humidity cm/cm/%RH$=1.0\times 10^{-5}$.

It has not been possible to control these factors. The temperature and relative humidity were recorded, however, and the difference between the exposure and the measuring never exceeded 4°C and 40%RH. The longest distance, measured on any of the films was 280 mm. The linear error of measurement, depending on the dimensional instability of the film, was calculated to be maximum ± 0.15 mm under the most unfavourable conditions.

The measuring error of the detail coordinatograph was max. ± 0.05 mm.

In order to get an idea as to the importance of these sources of error and the mathematical procedure, from the practical point of view, a plexiglass model was made with 28 inserted stainless steel balls. The model was radiographed and the primary data treated according to the same system as used for the specimens.

Eight exposures were performed with the model placed in various positions in front of the film. From the coordinates of the 28 primary measuring points, 14 distances were derived, the true lengths of which were unknown. Of the eight values obtained for each distance, a calculation was made for the mean, the standard error of the mean (s.e.m.) and the standard deviation (S.D.). Of the 14 values obtained of s.e.m. and S.D. a calculation was made for the mean and S.D. (Table 2).

Table 2.

	N	Mean	S.e.m.	S.D.
Standard deviation	14	0.083	0.000	0.036

If the variations in S.D. are used to find the reproducibility of the length determinations, the mean reproducibility will be 0.08. This means that the error of the measuring method with respect to the apparatus and the two primary geometrical formulae was less than 1/10 mm. The mean of the distances measured was 47.2 mm which gave a standard deviation of 0.2 per cent of the mean distance.

The same 14 distances were calculated on the coordinates of the same points in the secondary coordinate system. According to the definition, all these distances should be 40.0 mm. The mean of the 112 distances was 39.98 mm (s.e.m. 0.1 mm, S.D. 0.9 mm). The deviation from 40.0 mm was not significant. The standard deviation of the whole procedure, including all the geometrical calculations was thus 0.9 mm or 2.25 per cent of the defined distance.

B. Material

1. *Selection and Age Distribution*

The investigation included 28 cervical spines which were obtained from the Departments of Pathology, University City Hospital, Gothenburg.

The specimens were removed with surrounding musculature and immediately placed in plastic bags. If the examination could not be performed at once, the specimen was stored in a deep-freeze refrigerator at −25°C, but were thawed to room-temperature before testing.

The specimens were selected to a certain extent. Specimens from patients who had died in malignant diseases were avoided. Furthermore, all the specimens were rejected which on preparation or radiographic examination showed signs of other changes than degenerative. This meant that cervical spines with post-traumatic changes of the type luxations or subluxations were excluded.

Much care was taken to avoid damaging the bone structures, joint capsules or ligaments when collecting or preparing the specimens. If any lesion of this type was revealed, the specimen was rejected.

Age, sex and cause of death are tabulated (Table 3). The age of the deceased ranged from 11 to 67 years (mean age 52.0 years). Half of the series belonged to the age group 40–60 years.

2. *Classification of Degenerative Changes*

In order to correlate the variation in the pattern and the range of motion to degenerative changes, roentgenographic and macroscopic assessments were made.

Table 3.

Spec. No.	Age years	Sex	Cause of death
1	11	F	Cerebral ischemia
2	20	M	Bronchopneumonia
3	34	M	Cerebral tumor + circulatory failure
4	38	M	Pneumonia
5	46	F	Uremia
6	46	F	Intracranial art. aneurysm with haemorrhage
7	46	M	Cirrhosis of the liver
8	47	F	Aneurysm of basilary artery
9	48	F	Gastro-intestinal bleeding
10	48	M	Circulatory failure
11	50	F	Myocardial infarction
12	51	M	Myocardial infarction
13	53	M	Pneumonia
14	53	M	Cerebral thrombosis
15	55	M	Gastro-intestinal bleeding
16	55	F	Intracerebral bleeding
17	58	M	Pulmonary embolism
18	58	F	Myocardial infarction
19	61	M	Cerebral haemorrhage
20	62	M	Respiratory and circulatory failure
21	62	M	Myocardial infarction
22	64	M	Respiratory failure
23	65	F	Myocardial infarction
24	65	F	Peritonitis
25	65	M	Peritonitis
26	65	M	Myocardial infarction
27	65	F	Mb Sternberg + circulatory failure
28	67	F	Cerebral tumor + circulatory failure

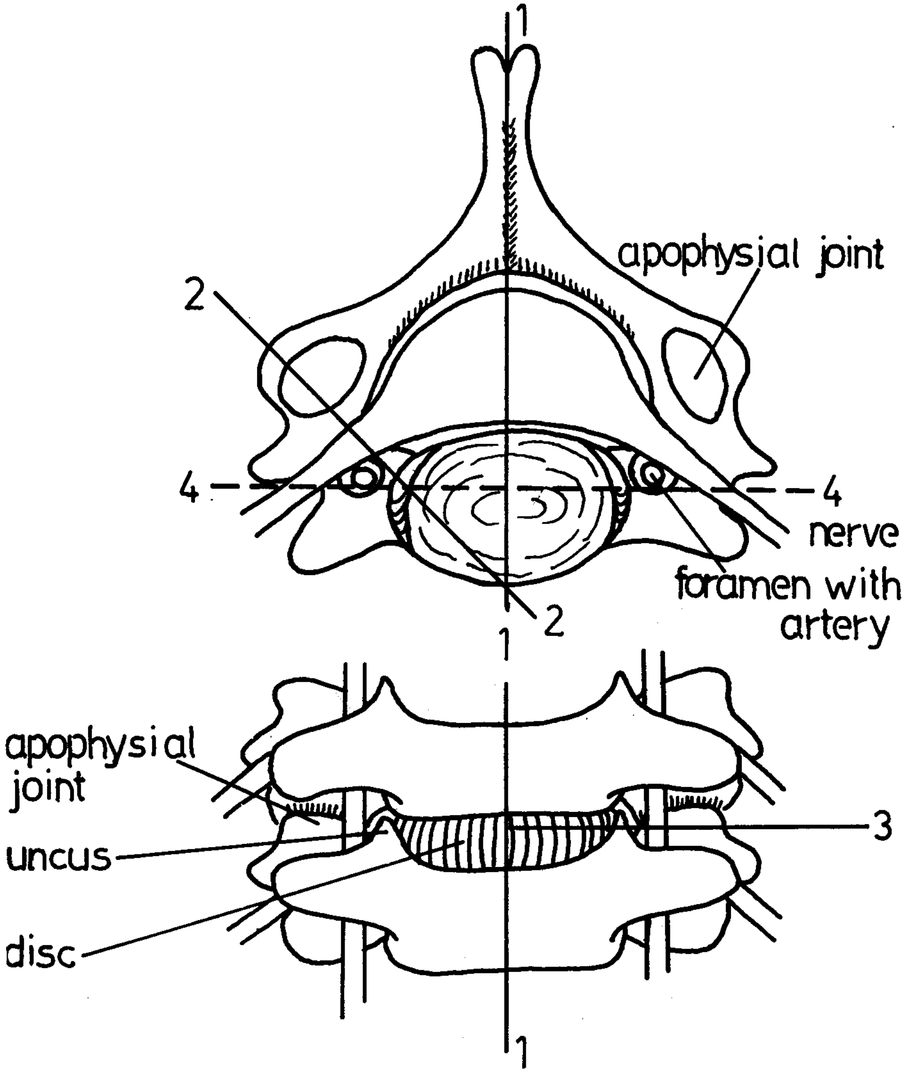


Fig. 8. Sketch showing how the specimens were cut. (*Hirsch et al.*, 1967. Repr. with permission of authors.)

The roentgenological changes were studied on the frontal and lateral views and on oblique views on which the specimen had been rotated 22.5° in either direction from the frontal view. The two latter projections gave a good view of the intervertebral joints.

Table 4. Grading of Degenerative Changes

Grade	Disc	Intervertebral Joint
	Macroscopic changes	
0	Normal disc. Shiny, white annulus and nucleus. Distinct border between annulus and nucleus.	Normal cartilage, shiny, smooth, white.
1	Lamellated, fibrous structure of annulus.	Rough, dry surface with small erosions.
2	Obvious, degenerative changes in nucleus and annulus. Fissures.	Pronounced erosions.
3	Marked degeneration in both annulus and nucleus. Ruptures and sequesters up to complete replacement of the nucleus by fibrous tissue.	Total destruction of cartilage.
	Roentgenographic changes	
0	Normal height. No osteophytes.	Normal joint space, no osteophytes.
1	Slight reduction of disc level. Minimal to small osteophytes.	Slightly reduced joint space. Small osteophytes.
2	Pronounced reduction of disc level. Moderate osteophytes. Slight subchondral sclerosis.	Reduced joint space. Moderate osteophytes and irregular cartilage-bone border.
3	Pronounced to total reduction of disc level. Large osteophytes.	Large osteophytes to roentgenologic anchylosis.

For the macroscopic evaluation, the specimens were cut according to the principles stated by *Hirsch et al.* (1967). An approximately 4 mm thick slab was cut from the sagittal plane of the entire specimen (Fig. 8:1). One of the halves was cut in the horizontal plane of each disc (Fig. 8:3), and the other vertically, through the uncus region (Fig. 8:2). Each disc, thus, was divided so that a cross-section through one half, a section of its sagittal extension and an oblique section through the other half were obtained. The cuts of the two specimen halves passed through the intervertebral joints on either side, which could easily be opened, allowing the joint cartilage to be examined.

The macroscopic assessment was concentrated on the condition of the disc and the joint cartilage, and the roentgenologic on the adjacent bone structure.

The condition of the disc was evaluated according to statements on lumbar discs, made by *Friberg & Hirsch* (1949–50) and *Hirsch & Schajowicz* (1952).

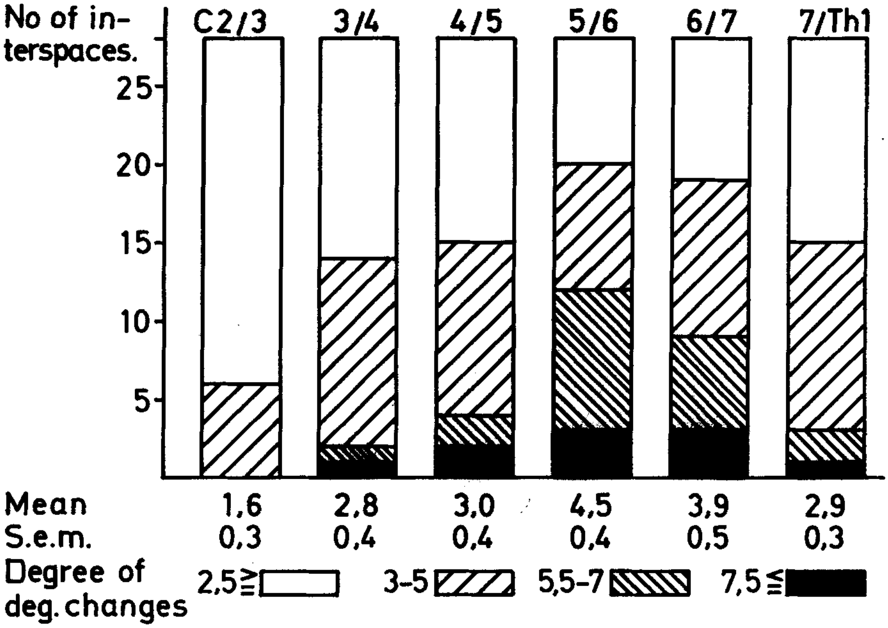


Fig. 9. Distribution of degenerative changes.

The limits between the various degrees, as illustrated in Table 4, are indistinct, but the purpose was not to give a detailed description of the degenerative changes, but instead to obtain a relative grading.

According to the table each disc and each intervertebral joint can receive 0–6 points. To prevent the degenerative changes of the intervertebral joints from being exaggerated in relation to the disc, the total of the two joints of each interspace was divided by two. By adding the points of the disc and the joints, each interspace may receive 0–12 points. The distribution of the degenerative changes on various segments is given in Fig. 9.

The figure shows that in the C5/6 interspace most of the degenerative changes were found, and that they decreased gradually with the distance from that interspace.

In order to check that the series similar to earlier investigations showed increasing degeneration with increasing ages (*Silberstein*, 1965; *Hirsch et al.*, 1967), and that the grading and the evaluation were correct, a T-test was performed. The specimens were divided into two groups, each including 14, one with ages ranging from 11–53 years, the other from 55–67 years. The degree of degeneration was compared in each interspace and in the entire specimen. The latter age group revealed at the 5%-level, significantly increasing degenerative changes in all the interspaces and in the entire specimen.

RESULTS

A. General Remarks

The results are based on approximately 100 000 primary measuring values, which after data processing resulted in x-, y- and z-coordinates for approximately 35 000 measuring points and the earlier described control angles.

These angles are calculated in all exposures and for the same vertebra vary only within a few tenths of a degree. Singular deviations above this limit are very large and obviously depend on error when measuring the radiograph or when punching the results. When a large deviation was found, the result of this exposure was rejected. If any vertebra was deformed under load, it seems reasonable to believe that the deformation is largest in the position where the specimen was subjected to the heaviest force, i.e. in the extreme positions of the movements. As a control, the angles in the neutral position and in the eight extreme positions were chosen in seven random selected specimens. In each vertebra, the mean, the s.e.m. and the S.D. for these nine pairs of angles were calculated. Of the 98 values, obtained for the s.e.m. and the S.D., the mean, the s.e.m. and the S.D. were calculated and compared with the values obtained in the same way for all the control angles of the plexiglass model. The differences are not statistically significant, and therefore it can be assumed that the vertebrae were not deformed outside the error of the method. Thus, in the following they can be regarded as rigid bodies.

The secondary coordinate system was drawn on transparent paper. The measuring points were inserted and their stepwise movements were indicated. In this way a diagram of motion was obtained.

The motion in the sagittal plane was plotted in the xy-plane (lateral view of the vertebra) and the xz-plane (the vertebra seen from above) of the secondary coordinate system (Fig. 10). Two diagrams were obtained, one for the motion from extreme extension to extreme flexion and one for the reverse motion.

The latero-flexion and the rotation were plotted in the yz-plane (front view of the vertebra) and the xz-plane of the coordinate system

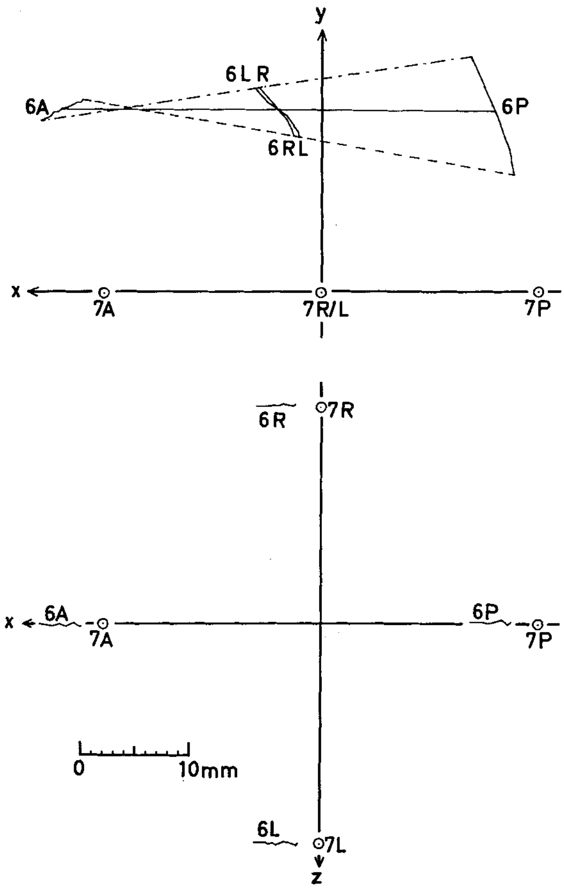


Fig. 10. Course of motion of measuring points in extension and flexion traced in the xy-plane (top) and the xz-plane. Point-dashed line indicates extreme flexion, dashed line indicates extreme extension, solid line neutral position.

(Fig. 11). Two diagrams were obtained of the latero-flexion, one for the motion from the extreme right to the extreme left side, and one for the reverse motion.

All the ranges of motion were indicated in angles and in relation to the neutral position of each vertebra. For calculation of the angles, the coordinates were used for the extreme positions of the measuring points. At motion in the sagittal plane, the A and P points were projected in the sagittal plane of the vertebra. At latero-flexion the R and L points were projected in the frontal plane (Fig. 12A), and at rotation in the horizontal

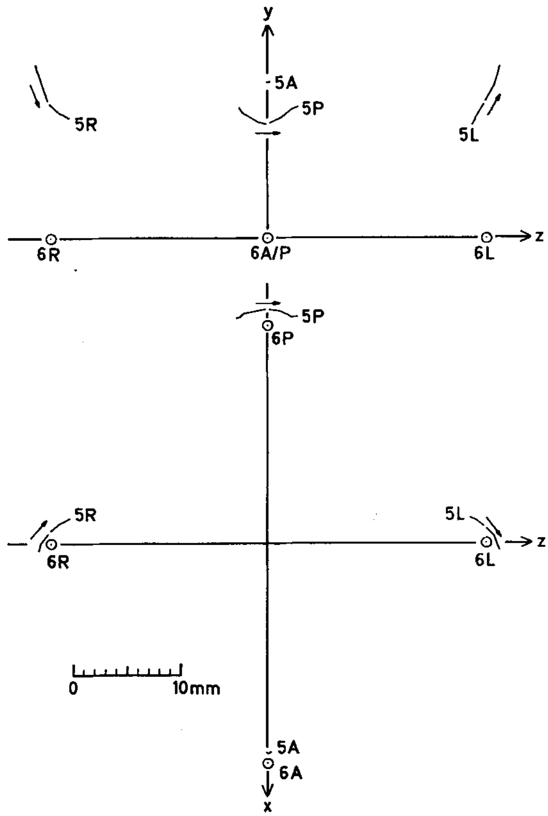


Fig. 11. Course of motion of measuring points in latero-flexion and rotation, traced in yz-plane (top) and xz-plane. Interruption in the courses indicates neutral position. Arrows indicate direction of motion from left to right latero-flexion.

plane, (Fig. 12B). Thus, the range of motion is expressed in the angle formed by the neutral position of the sagittal and the frontal axes, respectively, and the projection in each plane of the same axis after motion.

B. Pattern of Motion

1. *Sagittal Plane*

The two diagrams obtained from each vertebra of the motion in the sagittal plane were compared to each other. In no case of the entire series did these two diagrams of motion reveal different patterns, which

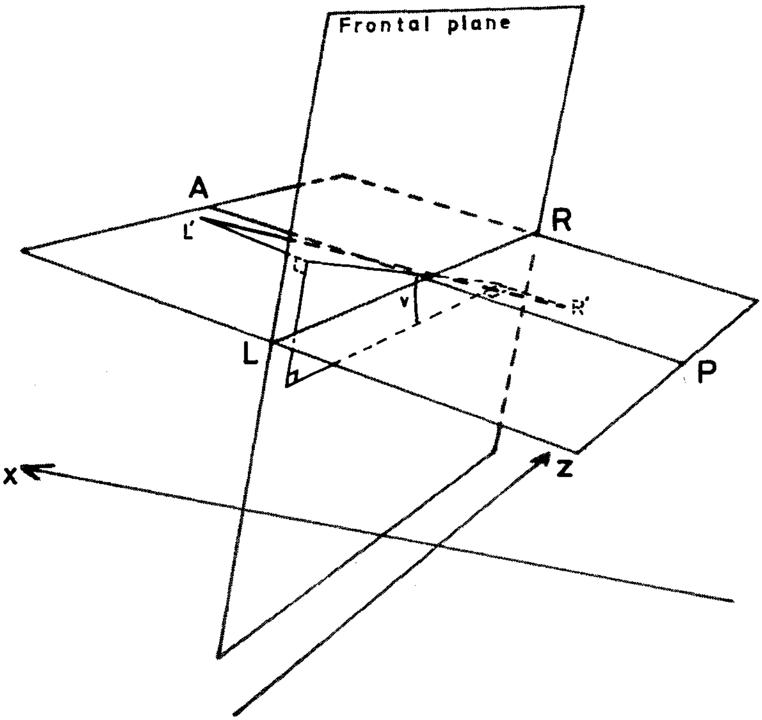


Fig. 12. A. Frontal axis in neutral position (R–L) and after motion (R'–L') and projections in frontal plane of R' and L'. V is the calculated angle at latero-flexion.

proved that the pattern of motion was independent of the direction of motion.

In all the interspaces examined, the extension was a combination of backwards tilting and backwards sliding. The flexion was a combination of forwards tilting and forwards sliding. All the points in the vertebra moved parallel to the sagittal plane (Fig. 13). Due to this, the centre of the motion must be an axis which is parallel to the frontal plane and situated in or under the vertebra.

If this axis is fixed, the course of each measuring point should constitute part of a circle. If the course of each measuring point is rectilinear, this means that the axis of motion moves. In order to find the centre of motion, *von Euler's* principle was employed: If a rigid body moves in one plane the centre of motion can be determined as the intersection between the mean centre proportionals of two lines, connecting the

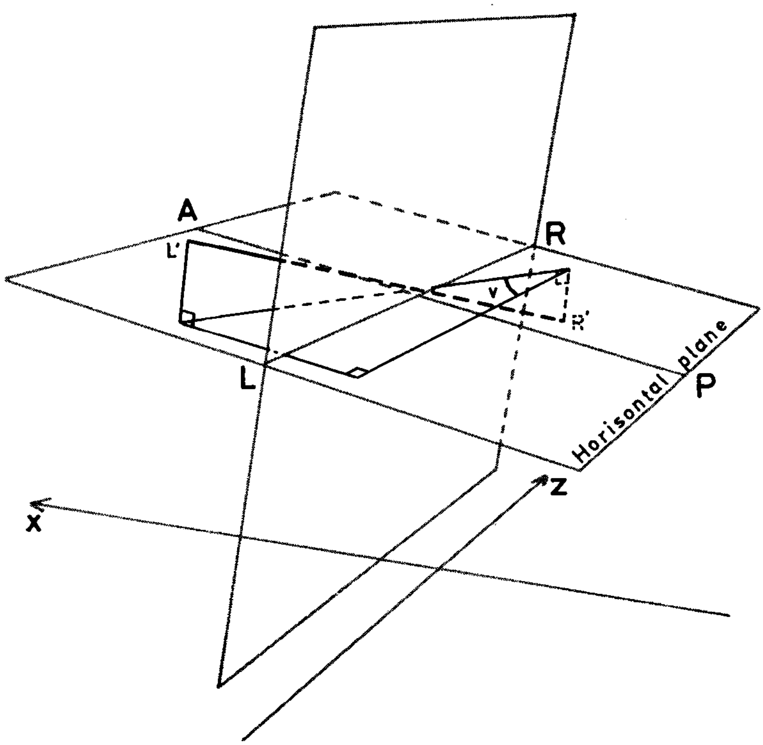


Fig. 12. B. R' and L' projected in horizontal plane and the calculated rotation angle V.

respective positions of two random selected points in two phases of the motion. The principle was used for each step of the motion in the sagittal plane (Fig. 14). The intersections will form a straight line, regularly situated within the subjacent vertebral body. In motion from extension to flexion, the axis moves from below posteriorly, upwards anteriorly, thus towards the concave side of the motion.

However, a detailed study of the diagrams shows that the courses of motion usually are rectilinear, but sometimes arched with the convexity towards or away from the vertebra. It has been impossible to determine whether the axis of motion is fixed or moves.

The distance of the axis from the vertebra decides the course of the motion. The closer the centre of motion is to the vertebra, the less the translation per degree of rotation, thus the steeper the course.

In order to obtain a relative measure of this, the so-called Top-angle

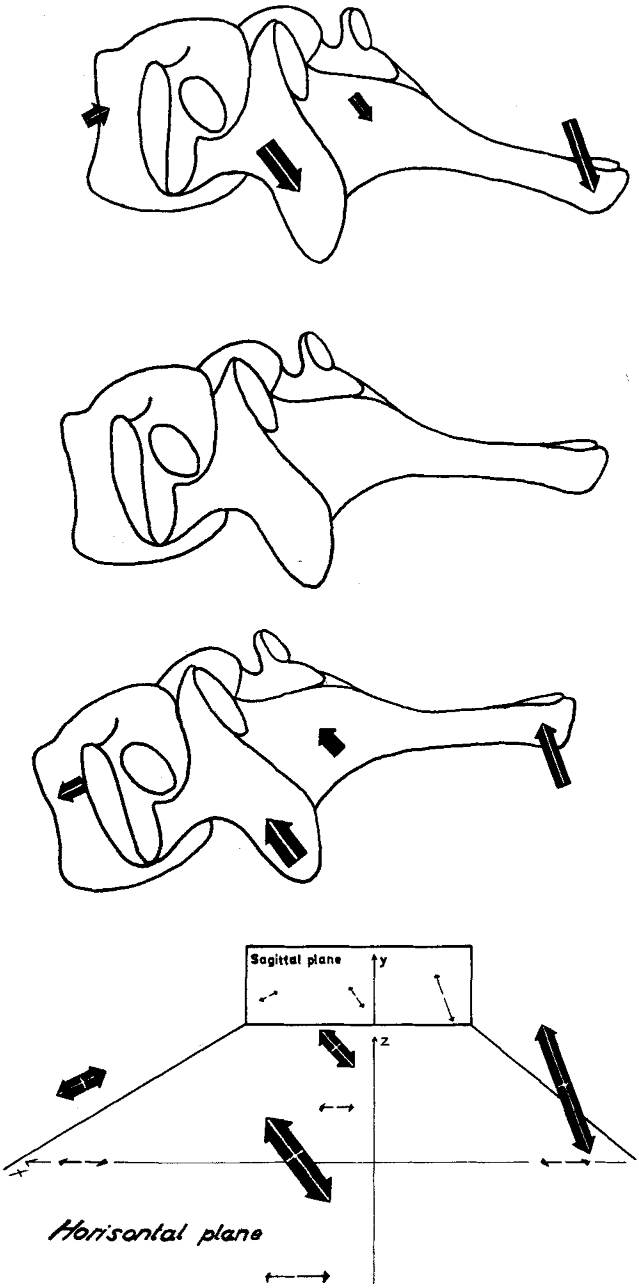


Fig. 13. The pattern of motion in the sagittal plane. From above: extension, neutral position and flexion. Bottom: motion projected in sagittal and horizontal planes.

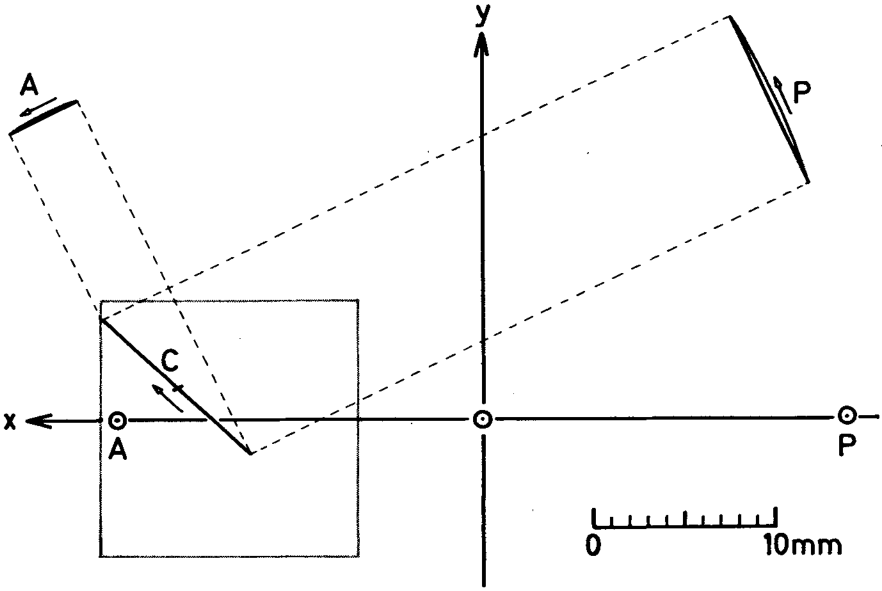


Fig. 14. Centre of motion if courses of measuring points are arched (dash at *C*) or if they are rectilinear (line at *C*). Subjacent vertebral body indicated in grey.

(T-angle) was constructed in each vertebra, as follows (Fig. 15). The courses of motion of the anterior and posterior measuring points were extended in a cranial direction and the angle formed was calculated. The larger the angle is, the more extensive the sliding of the vertebra will be in relation to its tilt. If the T-angle is 180°, there is no tilt, if the T-angle is 0° there is no sliding. The mean of the T-angles in the various interspaces, were compared in pairs, in the whole series (Table 5).

The T-angle of C2 is significantly larger than that of all the other vertebrae, and of C6 significantly less than that of all the others with the exception of C7. Furthermore, the T-angles of C3 and C4 are larger than the angle of C7.

Thus, the course of motion is the most flat in C2. C6 takes the steepest, and C7 the next steepest course while the courses of the remaining vertebrae are uniform. This means that the axis of motion of C2 is situated furthest distal to the vertebra and the axes of C6 and C7 lie closest to their respective vertebra.

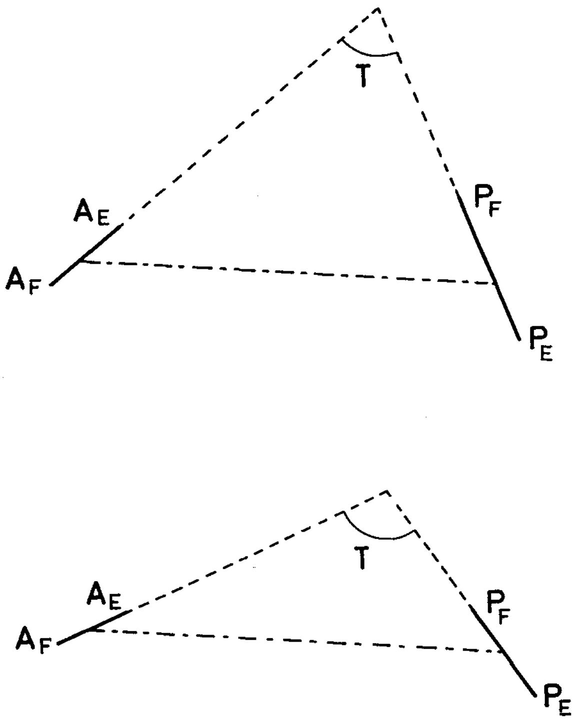


Fig. 15. Construction of T-angle. A_E—A_F and P_E—P_F are the courses of motion of the anterior and posterior measuring points. A small T-angle indicates a steep course of motion (top) and a large T-angle indicates a flat course (bottom).

Table 5.

Paired comparison of the Top-angle

	C2	C3	C4	C5	C6	C7
N	27	28	28	28	28	27
Mean	97.8	87.2	87.4	83.9	77.8	80.5
SD	9.2	8.2	7.5	8.7	8.0	8.7

T_{diff} at comparison of vertical to horizontal values

	C2	C3	C4	C5	C6
C3	4.1233***				
C4	4.5765***	−0.0811			
C5	8.6116***	1.4868	1.3039		
C6	5.7625***	4.3560***	4.6282***	2.7261*	
C7	7.2990***	2.9618**	3.1557**	1.4509	−1.1921

2P = 0.02*, 0.01**, 0.001***

Table 6.

Paired comparison of the ratio extension/flexion

	C2	C3	C4	C5	C6	C7
N	27	28	28	28	28	27
Mean	0.55	0.67	0.61	0.66	0.77	0.80
SD	0.41	0.33	0.27	0.28	0.31	0.38

T_{diff} at comparison of vertical to horizontal values

	C2	C4
C6	−2.2592*	−2.1533*
C7	−2.2690*	−2.1480*

2P = 0.05*. Only significant differences shown.

The ratio extension/flexion varies with each interspace (Table 6). The degree of flexion is always higher than that of extension, and the difference is most pronounced in the upper portion of the cervical spine. The flexion is almost double, as compared to extension in C2, while C6 and C7 reveal the relation 4:5. The individual variation, however, is very large and the differences are significant at the 5%-level, only when C2 and C4 are compared with C6 and C7.

The effect of degenerative changes on the pattern of motion was examined by studying the variations in the T-angle and the ratio extension/flexion.

Within each interspace the values were arranged according to the increasing degree of degeneration, and the least degenerated half was compared with the most degenerated.

On all levels the T-angle becomes reduced with increasing degeneration. Thus, the course of motion will be steeper with increasing degeneration. The *T*-test (Table 7) is not significant for any singular vertebra, but as they were all reduced, there is still a statistical significance at the 5%-level (Sign-test).

The ratio extension/flexion does not alter significantly, except for C5, where with increasing degeneration, the flexion becomes reduced in relation to the extension (Table 8).

2. *Frontal and Horizontal Planes*

The pattern of motion in these two planes are dealt with simultaneously as they are very uniform.

Table 7.

Variation of the T-angle with increasing degeneration.

	C2	C3	C4	C5	C6	C7
Deg. group	0.0–1.0	0.0–3.0	0.0–3.0	0.0–4.0	0.0–4.0	0.0–3.0
N	13	14	14	14	14	13
Mean	97.9	88.0	89.1	86.7	80.0	83.1
SD	7.3	6.7	6.9	7.6	5.3	9.0
Deg. group	1.5–5.0	3.0–9.0	3.0–8.0	4.0–9.0	4.0–8.0	3.0–7.5
N	14	14	14	14	14	14
Mean	97.6	85.5	85.7	81.1	75.6	78.0
SD	10.9	9.5	8.0	9.1	9.8	8.0
T_{diff}	+ 0.0877	+ 1.1082	+ 1.2195	+ 1.7831	+ 1.4721	+ 1.5707

Table 8.

Variation of the ratio extension/flexion with increasing degeneration.

Vertebra C5.

Deg. group	0.0 – 4.0	
N	14	
Mean	0.56	
SD	0.26	

Deg. group	4.0 – 9.0	
N	14	
Mean	0.77	
SD	0.26	
T_{diff}	– 2.1078*	2P = 0.05*

The two diagrams of the pattern of motion in the frontal plane were compared to each other, and in no case was there any difference in the pattern when the motion occurred from the right to the left, as compared to the reverse direction.

The motion in the frontal plane (Fig. 16) is a combination of lateral tilt and rotation in the same direction, i.e. latero-flexion to the right is combined with rotation to the right (clockwise) and latero-flexion to

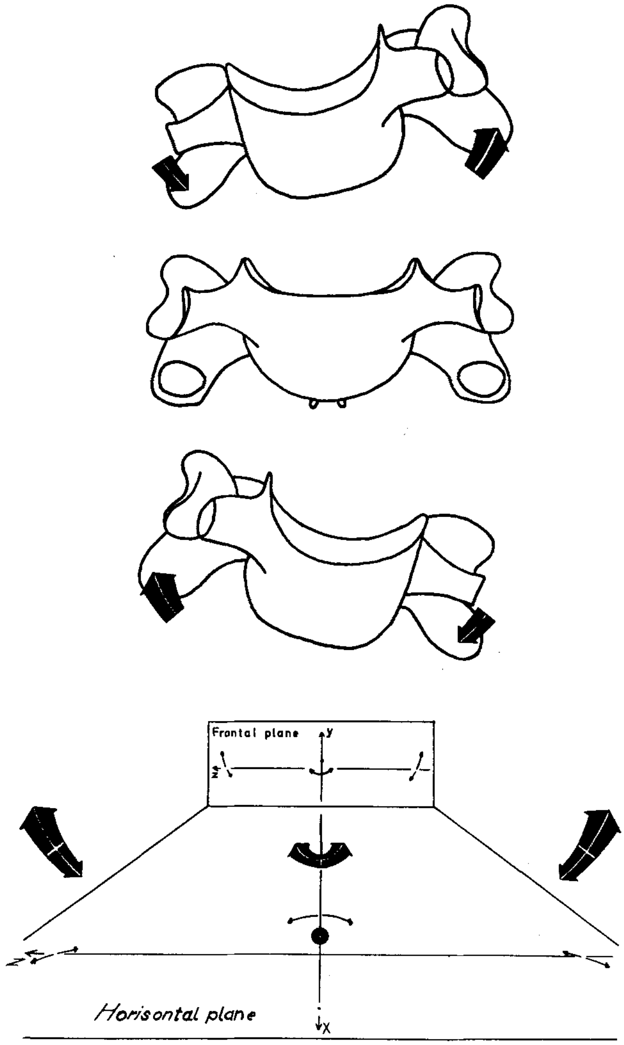


Fig. 16. The pattern of motion in the frontal and horizontal planes. From above: latero-flexion and rotation to the right, neutral position and latero-flexion and rotation to the left. Bottom: Motion projected in frontal and horizontal planes.

the left is combined with rotation to the left (anti-clockwise). The pattern of motion in the horizontal plane is the same as in the frontal plane.

The centre of motion in both planes is situated in the sagittal plane and in the anterior contour of the vertebral body. This was proved due to the position there of the anterior measuring point. In fact, on the diagrams of motion it is found that the anterior measuring point regularly is unmoved or has moved within a very limited space. The distance covered by the *A*-point from one extreme position to the other in latero-flexion and in rotation was calculated for all the vertebrae. The mean was 0.88 mm (s.e.m. 0.04, S.D. 0.42). Thus, the distance is very small and the anterior measuring point lies very closely to the centre of motion. It was also found that the other measuring points described arched courses with their concavity directed towards the *A*-point.

The proportion between latero-flexion and rotation when the specimen was latero-flexed, was obtained by dividing the latero-flexion by rotation, expressed in degrees. The ratio obtained, was compared in pairs (Table 9).

The rotation combined with latero-flexion was proportionally largest for C2, where the ratio was 3:2 and gradually diminished downwards in the cervical spine. In C7 the latero-flexion was 7.5 times larger than the rotation occurring at the same time. The difference is always statistically significant when a vertebra is compared with the vertebra two steps below.

Table 9.

Paired comparison of the ratio latero-flexion/rotation when the specimen is latero-flexed.

	C2	C3	C4	C5	C6	C7
N	26	27	28	28	28	26
Mean	1.47	1.84	1.75	2.66	2.73	7.48
SD	0.81	1.77	0.84	2.32	0.90	7.97

T_{diff} at comparison of vertical to horizontal values

	C2	C3	C4	C5	C6
C3	−0.9865				
C4	−1.2707	+0.2578			
C5	−2.4850*	−1.4297	−1.9563		
C6	−5.4224***	−2.3474*	−4.1672***	−0.1471	
C7	−3.8304***	−3.5900***	−3.8304***	−3.0708**	−3.1399**

2P=0.05*, 0.01**, 0.001***

Table 10.

Paired comparison of the ratio rotation/latero-flexion when the specimen is rotated.

	C2	C3	C4	C5	C6	C7
N	17	22	23	23	23	22
Mean	1.14	1.59	2.09	2.17	1.92	4.00
SD	0.43	1.03	1.08	1.73	1.40	4.12

T_{diff} at comparison of vertical to horizontal values

	C2	C3	C4	C5	C6
C3	−1.6824				
C4	−3.4357**	−1.6071			
C5	−2.4084*	−1.3773	−0.1917		
C6	−2.2144*	−0.9052	+0.4622	+0.5458	
C7	−2.8432**	−2.6676*	−2.1497*	−1.9585	−2.2915*

2P=0.05*, 0.01**

The ratio rotation/latero-flexion when rotating the specimen was compared in the same way (Table 10).

The latero-flexion combined with rotation was largest for C2 and least for C7. A comparison between the other vertebrae was not statistically significant.

The effect of the degenerative changes on the pattern of motion in the frontal and horizontal planes were studied by comparing the least degenerated half of the series with the most degenerated. Neither the distance of motion from one extreme position to the other, covered by the *A*-point, nor the ratio latero-flexion/rotation or rotation/latero-flexion revealed any statistically significant differences in any interspace.

C. Range of Motion

The values reported refer to the entire series, and it must be borne in mind that the series includes various degrees of degeneration. The ranges of motion cannot be regarded as mean values of spines with non-degenerated, unaffected discs.

The values of latero-flexion and rotation are the total of the range to the right and to the left.

Table 11.

Paired comparison of the range of motion in the sagittal plane

	C2	C3	C4	C5	C6	C7
N	27	28	28	28	28	27
Mean	4.9	10.2	13.0	14.5	13.5	8.0
S.e.m.	0.4	0.5	0.7	0.6	0.8	0.4
SD	2.2	2.7	3.5	3.2	4.4	2.6

T_{diff} at comparison of vertical to horizontal values

	C2	C3	C4	C5	C6
C3	−7.8293***				
C4	−10.1511***	−3.3205**			
C5	−12.8979***	−5.3631***	−1.6174		
C6	−9.1711***	−3.4052**	−0.4822	+0.9217	
C7	−5.2480***	+3.2442**	+6.2790***	+8.7424***	+5.8758***

2P=0.02*, 0.01**, 0.001***

1. *Sagittal Plane*

The mean of the total range of motion in the sagittal plane in this series was:

Extension 24° (s.e.m. 1°, S.D. 6°)
Flexion 40° (s.e.m. 2°, S.D. 8°)
Total 64° (s.e.m. 2°, S.D. 10°)

There were large individual variations.

The distribution of the total range of motion within the cervical spine varied (Table 11). The range of motion was least in C2 and increased in C7 and C3 in the order mentioned. The middle cervical vertebrae C4, C5, and C6 had the most equal and the largest range of motion.

A comparison of the range of motion in each interspace between the most degenerated and the least degenerated half of the series did not reveal any statistically significant differences at any level, neither in extension, flexion nor total motion. In order to control this result, the series was divided into several small groups, with regard to the degree of degeneration, and a variance-analysis was performed. There were no criteria of the degree of degeneration having any effect on the range of motion.

2. *Frontal Plane*

There was no difference in this series between the range of motion to the right and to the left.

As the intersegmental range of motion, when the specimen was latero-flexed, was related to the neutral position of each vertebra, it was not geometrically correct to add together the intersegmental ranges of motion in order to obtain the total range. As the deviation was small, the addition was still made and the mean values obtained:

Latero-flexion 49° (s.e.m. 3°, S.D. 14°)
Combined rotation 28° (s.e.m. 2°, S.D. 8°)

There were large individual variations.

The intersegmental range of motion had a comparatively even distribution with the exception of C7 which moved less than the others (Table 12). The rotation combined with latero-flexion was unevenly distributed in the cervical spine (Table 13). The proportional relation has been indicated in Table 9 (Page 49).

There were no statistically significant differences when the intersegmental range of motion in the least degenerated half of the series was compared with the most degenerated.

3. *Horizontal Plane*

The total range of motion, when the specimen was rotated, was calculated in the same way as when it was latero-flexed and the mean values were:

Rotation 45° (s.e.m. 5°, S.D. 18°)
Combined latero-flexion 24° (s.e.m. 3°, S.D. 10°)

Also in this plane the individual variation was very large. The intersegmental distribution revealed that the range of motion was largest in C4 and least in C2, C6 and C7 (Table 14).

The mean of the latero-flexion, combined with rotation, was largest in C3 and least in C7 (Table 15). The ratio has been indicated in Table 10 (Page 50).

No statistically significant differences could be demonstrated in this plane of motion either in a comparison between less or more degenerated interspaces.

Table 12.

Paired comparison of the range of motion in the frontal plane

	C2	C3	C4	C5	C6	C7
N	26	27	28	28	28	26
Mean	7.9	9.8	9.1	9.0	8.4	6.3
S.e.m.	0.6	0.6	0.6	0.5	0.6	0.4
SD	2.9	3.4	2.9	2.7	3.4	2.2

T_{diff} at comparison of vertical to horizontal values

	C2	C3	C4	C5	C6
C3	−2.2300*				
C4	−1.5028	+0.8534			
C5	−1.4210	+1.0087	+0.1367		
C6	−0.5941	+1.5333	+0.7936	+0.6942	
C7	+2.2516*	+4.4963***	+3.9228***	+3.9717***	+2.6746**

2P=0.05*, 0.01**, 0.001***

Table 13.

Mean values of the rotation combined with latero-flexion when the specimen is latero-flexed

	C2	C3	C4	C5	C6	C7
Mean	6.1	6.8	6.1	4.7	3.4	2.0
S.e.m.	0.4	0.5	0.5	0.4	0.3	0.4
SD	2.6	2.8	2.5	2.3	1.8	1.8

Table 14.

Paired comparison of the range of motion in the horizontal plane

	C2	C3	C4	C5	C6	C7
N	17	22	23	23	23	22
Mean	6.0	9.8	10.3	8.0	5.7	4.7
S.e.m.	0.8	1.1	0.9	0.8	0.9	0.4
SD	3.4	4.9	4.1	3.9	4.3	1.9

T_{diff} at comparison of vertical to horizontal values

	C2	C3	C4	C5	C6
C3	−2.7170**				
C4	−3.5594**	−0.3936			
C5	−1.7373	+1.3334	+1.9515		
C6	+0.1930	+2.9448**	+3.7116***	+1.9020	
C7	+1.4400	+4.4834***	+5.8553***	+3.5956***	+0.9985

2P=0.01**, 0.001***

Table 15.

Mean values of the latero-flexion combined with rotation when the specimen is rotated

	C2	C3	C4	C5	C6	C7
Mean	5.4	6.8	5.7	4.5	3.7	2.0
S.e.m.	0.7	0.8	0.7	0.6	0.5	0.3
SD	2.7	3.5	3.1	2.7	2.6	1.3

D. Conclusions and Discussion

1. *Pattern of Motion*

The patterns of motion in the cervical spine are of two entirely different types. In the sagittal plane the motion is limited to one plane, i.e. each point in a vertebra moves parallel to the sagittal plane. The motion can be described as a rotation in this plane around an immobile or mobile axis which is perpendicular to the plane.

In the frontal and the horizontal planes, the motion, on the other hand, occurs in several planes, but is symmetrical in relation to the sagittal plane and, therefore, can be described as a rotation around a point in this plane.

These two types of motion are controlled by the shape of the discs and the intervertebral joints. As the system of an ideal case is symmetrical with respect to the sagittal plane, but asymmetrical with respect to the other two planes, it is reasonable to expect different patterns of motion. In principle, the patterns of motion observed, do not differ from those reported by other authors (cf. Review of Literature).

The axis of motion in the sagittal plane was found to lie in the subjacent vertebral body, however, on different levels in different segments. The size of the Top-angle (Page 44) shows that the axis of the C2 motion lies further distal than those of C6 and C7. This finding is in accordance with *Penning's* (1968) positioning of the C2 axis of motion caudal in the C3 vertebral body and the C6 axis cranial in the C7 vertebral body. It has been impossible to decide whether the axis of motion is immobile or whether it moves.

The centre of motion in the frontal and horizontal planes proved to lie in the anterior contour of the vertebra and in the sagittal plane. The diminutive movement, less than one millimeter, made by the anterior measuring ball at motion from one extreme position to the other, for obvious reasons depends on the impossibility of placing the ball right in the centre of motion.

The position of this centre has not been mentioned in earlier literature. *Bakke* (1931) however, observed that a vertebra in latero-flexion slides on the subjacent vertebra towards the convex side. This is in good accordance with a centre of motion placed anteriorly to the joint processes, the latter of which at rotation are turned forwards on the convex side and on a frontal view are projected further lateral than the processes of the subjacent vertebra.

As mentioned earlier, the Top-angle is a measure of the shape of the course of motion in the sagittal plane. The proportion between latero-flexion and rotation, when the specimen is latero-flexed, is a measure of the shape of the course of motion in the frontal and horizontal planes. If latero-flexion occurs without simultaneous rotation, the motion is limited to one plane and the ratio is infinite (latero-flexion $x°$, rotation $0°$. $\frac{X}{0}$=infinity). If the latero-flexion and the rotation are equal, there will be equal motion in both planes and the ratio will be 1. The same reasoning can be applied to the ratio rotation/latero-flexion when the specimen is rotated.

C2 has the largest Top-angle and at the same time the lowest ratio of latero-flexion/rotation and rotation/latero-flexion. This means that C2 at the same time has the most flat course of motion in the sagittal plane, the largest rotation combined with latero-flexion and the largest latero-flexion combined with rotation. There is a complete reverse condition for C7.

The tendency, for the vertebrae lying in between, even if it is not statistically significant in all details, is that the T-angle becomes reduced and the two ratios increase gradually down the cervical spine.

The above statement can be regarded as a proof that the freedom of motion, found in a vertebra as related to the subjacent one, is largest in the upper portion of the cervical spine and becomes reduced in a distal direction. It was also found that the flexion proportionally was the largest in C2 and became reduced in a distal direction.

Degenerative changes affect the pattern of motion only with respect to the course in the sagittal plane, and the proportion between extension and flexion in the interspace of C5/6.

The course of motion is statistically significant steeper with increasing degeneration, and in analogy with the above statements, this implies that the freedom of motion of the vertebrae in relation to the subjacent one becomes reduced with increasing degeneration.

The fact that the flexion was reduced in relation to the extension only in C5, may depend on the most pronounced changes in the series being found there.

2. *Range of Motion*

There were large individual variations in all directions of the range of motion in the cervical spine.

The means of the intersegmental range of motion in the sagittal plane and at latero-flexion lie within the limits found on earlier studies of specimens, but at rotation the mean is lower.

In the sagittal and the horizontal planes, the intersegmental range of motion is largest in the middle parts of the cervical spine, while the motion in the frontal plane is more evenly distributed.

Contrary to most of the earlier investigations, there is no correlation between reducing range of motion and increasing degeneration. This applies to all directions of motion, to all interspaces, and also to the total motion of the specimens.

Galante (1967) stated regarding the annulus fibrosis in the lumbar spine that "after the middle of the third decade no significant changes in tensile properties were present as a function of aging".

It is true that *Galante's* results deal with the lumbar spine, but if his findings can be applied to the cervical spine, this may partly explain why the range of motion is not affected by degenerative changes in the present series in which all specimens, except two, were obtained from deceased persons older than 30 years.

Furthermore, *Hirsch & Lewin* (1968), when studying the range of motion in the lumbo-sacral synovial joints, found that disc degeneration did not affect the excursion of the L5 facet relative to the sacrum.

However, it is not sure that changes in the morphology of the disc and the intervertebral joints cause a reduction of the range of motion. *Schoening & Hannan* (1964) measured the total range of motion of the cervical spine in living subjects by means of a 17″ wand firmly fixed to the occiput. Even if the method has large sources of error, there was no correlation between the range of motion, in the first place, and interspace narrowing in one level, posterior bar, or apophyseal arthritis on one or many levels, in the second place. Contrary to this, pain in the neck, arms and upper trunk, tenderness over the articular masses and spinal processes, pain with passive neck motion or increased muscularity caused reduced range of motion.

SUMMARY

The primary intention was to demonstrate the intersegmental pattern of motion in the cervical spine and, therefore, an apparatus for three-dimensional radiographic examination of autopsy specimens was designed.

The series consisted of 28 autopsy specimens, including C3–Th1, in the age groups 11–67 years. The specimens were indicated with steel balls and tested for the pattern of motion in the sagittal-, frontal- and horizontal planes. The motion in each plane was represented by a number of stepped movements.

After data processing including a number of geometrical transformations, motion diagrams were drawn.

The motion in extension-flexion was parallel to the sagittal plane, and made its course around an axis in the subjacent vertebral body, perpendicular to this plane. The appearance of the course varied between the different interspaces. Increasing degenerative changes affected the pattern of motion in the sagittal plane so that the freedom of motion between the vertebrae was reduced.

The patterns of motion in latero-flexion and rotation were similar to each other. One movement is always combined with the other and there is only a difference in the proportion between latero-flexion and rotation when the specimen is latero-flexed or rotated. The centre of motion is a point situated in the anterior contour of the body of the moving vertebra and in the sagittal plane. The pattern of motion in the frontal and horizontal planes were not affected by degenerative changes.

The maximum ranges of motion in all planes were calculated, and the results lay within the limits earlier found on examinations of specimens except for the rotation which in this series was lower.

Degenerative changes had no effect on the range of motion in any planes or in any interspaces.

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